CATHODIC PROTECTION/PARTIAL COATINGS VERSUS COMPLETE COATINGS IN TANKS

MAY, 1982

Prepared By:
OFFSHORE POWER SYSTEMS DIVISION
Westinghouse
In Cooperation with
Avondale Shipyards, Inc.

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
MAY 1982	**N/A**	**-**

4. TITLE AND SUBTITLE	
Cathodic Protection/Partial Coatings Versus Complete Coatings in Tanks	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tools Building 192 Room 128 9500 MacArthur Bldg Bethesda, MD 20817-5700**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**72**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

FOREWORD

This research project was performed under the National Shipbuilding Research Program. The project, as part of this program, is a cooperative cost shared effort between the Maritime Administration and Avondale Shipyards, Inc. The development work was accomplished by Offshore Power Systems under subcontract to Avondale Shipyards. The overall objective of the program is improved productivity and, therefore, reduced shipbuilding costs to meet the lower Construction Differential Subsidy rate goals of the Merchant Marine Act of 1970.

The studies have been undertaken with this goal in mind, and have followed closely the project oultine approved by the Society of Naval Architects and Marine Engineers' (SNAME) Ship Production Committee.

Mr. Benjamin S. Fultz of Offshore Power Systems served as Project Manager and principal investigator. Mr. Paul W. Michael and Mr. Robert L. Burgett, also of Offshore Power Systems, performed the economic analysis. On behalf of Avondale Shipyards, Inc., Mr. John Peart was the R&D Program Manager responsible for technical direction, and publication of the final report. Program definition and guidance was provided by the members of the 023-1 Surface Preparation Coatings Committee of SNAME, Mr. C. J. Starkenburg, Avondale Shipyards, Inc., Chairman.

We wish also to acknowledge the support of Mr. Jack Garvey and Mr. Robert Schaffran of the Maritime Administration.

Special thanks are given to Mr. George W. Kurr of Federated Metals Corporation for supplying anode materials and technical advice on cathodic protection calculations. Thanks are also given to the following listed corporations for technical data and materials for testing:

Bywater Coatings
Clearkin Chemical Corporation
Delta Lines

Dow Chemical U.S.A.

Engelhard Industries Division

Esgard

Eureka chemical Company

Exxon International

Farboil

Lykes

Magnus Maritec International, Inc.

Mobile Chemical

Sanchem, Inc.

Sentry Paint and Chemical Company

Sigma Coatings, Inc.

Waterman Steamship Corporation

Executive Summary

ship ballast tanks are one of the most costly, time delayig components of new ship construction. In addition, ballast tanks are one of the most severe corrosion areas during ship operations and as a result, contribute significantly to high maintenance cost and ship nonavailability.

The 023-1 Panel of SNAME recognized these problems and selected a research and development project to investigate alternate, cost effective corrosion control solutions. Four approaches were selected for meek-up ballast tank testing and 20 year life cycle cost analysis.

- Completely coated tanks with high performance coatings
- Partially coated tanks with cathodic protection
- Soft coatings with cathodic protection
- Preconstruction primer with cathodic protection

Of of the systems evaluated, the preconstruction primer with cathodic protection was the best performer, least expensive initially and least expensive over the 20 year economic life of the ship. Partial coatings with cathodic protection performed as well as complete matings and were more cost effective. The soft coatings performance with cathodic protection was suspect. Five of the six screened soft coating systems either failed or marginally passed.

Certain prerequisites were also found to be necessary to assure successful cathodic protection perfomance. Tanks must be “pressed-up” With salt water ballast.

In conclusion, this project achieved all project goals. Identification was made of ballast tank corrosion protection approaches which are effective in mitigating corrosion and yet save new instruction and operating dollars.

TABLE OF CONTENTS

	Page
Foreword	i
Executive Summary	iii
Table of Contents	iv
List of Figures	v
List of Tables	vi
1. Conclusions	1-1
1.1 Project Results	1-1
1.2 Cost Savings	1-3
1.3 Continued Research	1-3
2. Project Plan of Action and Results	2-1
2.1 Background Technical Information	2-1
2.2 Plan of Action	2-2
2.3 Results	2-3
2.3.1 Discussion of Historical System Performances	2-3
2.3.1.1 High Performance Coating System	2-3
2.3.1.2 Partial Coatings of Tanks Combined with Cathodic Protection	2-4
2.3.1.3 Soft Coatings plus Cathodic Protection	2-7
2.3.1.4 Preconstruction Primer Plus Cathodic Protection	2-8
2.3.1.5 Summary	2-9
2.3.2 Tank Test Results	2-10
2.3.2.1 Performance of Tank 1 - Aluminum Anode with Partial Coatings	2-13
2.3.2.2 Performance of Tank 2 - High Performance Coatings	2-14
2.3.2.3 Performance of Tank 3 - Zinc Anode with Partial Coatings	2-14
2.3.2.4 Performance of Tank 4 - Preconstruction Zinc Primer plus Aluminum Anode	2-14
2.3.2.5 Performance of Tank 5 - Preconstruction Primer Only	2-19
2.3.2.6 Performance of Tank 6 - Preconstruction Primer Plus Zinc Anode	2-21
2.3.2.7 Performance of Tanks 7, 8 and 9 - Soft Coatings With and Without Cathodic Protection	2-22
2.3.3 Anode Performance	2-24
2.3.4 Economic Analysis	2-30
2.3.4.1 Initial Construction Assumptions	2-30
2.3.4.2 High Performance Coatings Assumptions	2-33
2.3.4.3 Partial Coatings with Cathodic Protection	2-33
2.3.4.4 Soft Coatings with Cathodic Protection	2-33
2.3.4.5 Preconstruction Primer with Zinc Anodes	2-34
2.3.4.6 General Assumptions	2-34
2.3.4.7 Explanation of Economic Analysis Method	2-35
2.3.4.8 Results of Analysis	2-35

Annex A - Bibliography
Annex B - American Bureau of Shipping Letter
Annex C - United States Coast Guard Letter

LIST OF FIGURES

		Page
2.1	Photograph of One Test Tank Assembly	2-10
2.2	Drawing Showing Details of Test Tank Assembly	2-11
2.3	Photographs of Aluminium Anode/Partial Coatings at One Year	2-15
2.4	Photographs of High Performance Coatings at One Year	2-16
2.5	Photographs of Zinc Anode/Partial Coatings at One Year	2-17
2.6	Photographs of Zinc Primer/Aluminum Anode at One Year	2-18
2.7	Photographs of Preconstruction Primer Only at One Year	2-19
2.8	Photographs of Preconstruction Primer/Zinc Anode at One Year	2-20
2.9	Photograph of Air Pocket Corrosion	2-21
2.10	Soft Coatings Screening Results	2-23
2.11	Close-up Photographs of Anodes After One Year	2-31
2.12	Comparison Photograph of Anodes After One year	2-32

LIST OF TABLES

		Page
Table I	Corrosion Control Alternates Used In Tank Test	2-12
Table II	Test Site Sea Water Information	2-13
Table III	Half Cell Potentials ($Cu/Cuso_4$)	2-13
Table IV	Basic Properties of Anodes in Sea Water	2-24
Table V	Anode Performance Summary (12 months)	2-29
Table VI	Summary of Economic Analysis	2-36
Table VII	Listing of Proven Corrosion Control Alternatives in Ballast Tanks by Least Expensive Approach	2-38

SECTION 1
Conclusions

1. Conclusions

1.1 Project Results

The objective of this project was to evaluate the technical feasibility and economics of using a combination of cathodic protection and partial coatings in lieu of a complete coating of ballast tanks with high performance coatings. To accomplish this objective, three distinct tasks were performed:

- Data Collection and Analysis
- Laboratory Testing
- Economic Analysis (20 year life cycle cost of each approach).

Based on the results of initial data collection concerning probable system performances, a laboratory test program was formulated and presented to SNAME Panel 023-1 for approval. The approved test program consisted of four corrosion control alternates for evaluation. These were:

- Ballast tanks completely coated with high performance coatings (Baseline)

- Ballast tanks partially coated with high performance coatings plus cathodic protection

- Ballast tanks completely coated with soft coatings plus cathodic protection

- Ballast tanks preconstruction primed plus catholic protection

Both aluminum and zinc sacrificial anode systems were evaluated.

To test the proposed alternates, actual mock-up test tanks were constructed which duplicated ballast tank configurations. These test tanks were then ballasted and deballasted every 30 days for one year (20 days full and 10 days empty). At the end of one year, each alternate was graded. The results of these tests are as follows:

- Preconstruction primer with zinc anode was the best performer.
- Zinc anodes outperformed aluminum anodes.
- Partial coatings with cathodic protection provided adequate corrosion protection.
- All anodes performed better than theoretical.
- Soft coatings with cathodic protection are suspect -- five of six screened coatings either failed or marginally passed.

Simultaneous with the test program, a search was made to determine probable system performance based on historical data. Following the tank testing phase, cost data was also collected. The historical data, cost data and tank test results were then used to formulate a 20 year life cycle cost analysis. The results of this analysis are as follows:

- Preconstruction primer with cathodic protection is the least costly alternate initially.
- Preconstruction primer and soft coatings are the least expensive over twenty years.
- Partial coatings with cathodic protection are less costly initially and at 20 years than the baseline, high performance approach.

In conclusion, both preconstruction primer and partial matings systems are viable, cost effective approaches to ballast tank corrosion protection.

1.2 Cost Savings

If the preconstruction primer with cathodic protection approach is selected over the baseline, high performance system, approximately $150,000 can be saved in initial construction dollars and $270,000 in total life cycle cost. If partial coating with cathodic protection is selected in lieu of total coatings, at least $32,000 can be saved initially and $190,000 over twenty years.

1.3 Continued Research

The tank tests intiated as a part of project should be continued to verify the assumptions made in the economic analysis. The soft coatings with cathodic protection should be restarted with a cathodic protection compatible coating. The progress of this test program should be reported on an annual basis and continued for at least five and preferably eight years.

SECTION 2

Project Plan of Action & Results

2. Project Plan of Action and Results

2.1 Background Technical Information

When steel is produced, energy is consumed to elevate the iron oxide in ore to a higher energy state. As with all things in nature, the produced steel tends to return to a lower energy state by recombining with oxygen to form oxides of iron. The visible result of this phenomena is the corrosion or rusting of processed steel. As the steel corrodes, it loses structural integrity and an ability to perform an intended purpose.

Fran the time man made the first steel ship, he has been plagued with arresting the wasting away of metal. Many techniques have been attempted to control this corrosion, but none have totally solved the problem.

In general, three coalitions are necessary for steel to corrode: the steel is Unprotected, oxygen is present, and an electrolyte is available to allow or promote the flow of electrons necessary to achieve the chemical combination of iron and oxygen into an oxide of iron. Neutral iron changes to positive iron by the loss of electrons through the electrolyte medium. The resulting positive iron then combines with free oxygen to form iron oxide (rust).

$$\text{Fe (metal)} = \text{Fe}^{+2} \text{ (ion)} + 2\text{e (electrons)}$$
$$\text{Fe}^{+2} + \text{O}^{-2} = \text{FeO (Oxides)}$$

One method of controlling corrosion is by placing a barrier or insulator between the iron and oxygen. Protective coatings perform this purpose with varying degrees of success.

Another method is to provide an excess number of electrons to the iron which can be lost without changing the electrical charge of the iron. Cathodic protection performs this function.

Probably the most direct approach to solving the corrosion problem is to use steel of sufficient thickness to allow for corrosion loss over the designated design life of the structure. The iron is allowed to corrode without much concern being given to the wastage. All ship regulatory agencies recognize the problem of corrosion and have established requirements to allow for the loss of strength through corrosion. However, if corrosion control techniques are used, special dispensations are given concerning required steel corrosion allowance. For example, Section 22, "Vessels Intended to Carry Oil in Bulk," of the American Bureau of Shipping Rules for Building and Classing Steel Vessels, allows an average steel scantling reduction of 10% (but not more than 3mm) when special protective coatings are adopted for corrosion control.

Corrosion control techniques for ballast tanks have significantly improved during the last 20 years. New coatings have been developed and in-service tested.[8,10,12,13,25] Catholic protection has advanced from a black magic art to a science.[6,24] These developments are the reason for the allowances in scantling reduction discussed above.

2.2 Plan of Action

The purpose of this study was to perform a technical feasibility study and economic analysis of various selected ballast tank corrosion control techniques. To accomplish this purpose, the following actions were completed:

- Data Collection and Evaluation
- Laboratory Testing
- Economic Analysis

The data collection and evaluation consisted of literature reviews and discussions with known experts. The type of data collected included such things as:

- Repair Cost (Drydocking fees, etc.)

- Coatings Cost for New instruction (Both High Performance and Soft Coatings)
- Coatings Cost for Renewal of In-service Coatings
- Coatings Performance Data (Life)
- Cathodic Protection Cost (Installation, maintenance, and utility)
- Cathodic Protection Performance Data
- Combination of Coatings and Cathodic Protection Performance Data

This data was then used to formulate a laboratory test program and to perform an economic analysis (20 year life cycle cost). Corrosion control techniques studied included the following:

- Partial Coating (High Performance) Plus Catholic Protection
- Preconstruction Primer (Inorganic Zinc) plus Cathodic Protection.
- soft Coatings Plus Cathodic Protection
- High Performance Protective coatings

2.3 Results

2.3.1 Discussion of Historical System Performances

2.3.1.1 High Performance Coating Systems

At one time, high performance tank coatings were envisioned as “the solution” for corrosion protection. The manner in which coatings are applied tends to be a significant factor in the ability of coatings to perform as a viable corrosion protection device. Experience proves this is difficult to administer. Usually, the more sophisticated the mating, the more stringent the control requirements become during application. Temperature, humidity, ventilation, time of cure, and accessibility to craft personnel must all be considered. These points must be taken into account when specifying and applying high performance matings. Controls must be built in, and accessibility must be designed into the vessel in parallel with other cost considerations. Too many times, applicators consider all paint as being the same. Unfortunately, procedures for application developed and used in the 1940's are considered by some to be adequate for present day matings. This misconception is being recognized and a slow change in practice is now taking place.

With any discussion of corrosion control alternatives, one major question which must be answered concerns systems performance or life. Briggs[12] wrote, "It may be stated that a 10 to 20 year service life for tank coatings is within the realm of possibility." He goes on to cite an example of a system of inorganic zinc plus one coat of epoxy which performed for 53 months with minimun touch-up. A U.S. Department of Commerce study[17] cites 6 year satisfactory performance. Matanzo[29] reports some service histories of coal tar epoxy with 98% intact paint after 5.5 years and some epoxy systems with 74% to 98% intact paint after approximately 7 years. The mean performance of the epoxy system was 88%. Fultz[19] compiled 36 case histories of ballast tank paint performances. Eleven of these cases were evaluated 5 years after initial application. With the exception of one ship, 1% was the average failure. The one exception was 10% failure in 5 years. Two ships were reported as having 5 and 10 percent failures after 12 years.

Consultation with port engineers and resident shipowner corrosion engineers revealed the same relative performance as discussed above. One cited 2% failure at 5 years With was then repaired and an additional 5% failure at 10 years. Another cited system performance of 8 to 10 years with no maintenance and complete renewal at the end of 10 years. Fran this data, it can be conservatively projected that high performance systems will continue to protect salt water ballast tanks for at least 10 years.

2.3.1.2 Partial Coating of Tanks Combined with Cathodic Protection

Cathodic protect ion is another approach to protect steel tanks.[6,12,33,34] For catholic protection to function, a steady current flow is required between the anode (attached to steel) and the cathode (steel beinq protected). This current flow is dictated by the resistance of the electrolyte. Stagnant, fresh water is a poor electrolyte and air is an even poorer one. Salt water (sea water) is a good electrolyte and most cathodic protection systems are designed for use in sea water. Where cathodic protection is used, the ship inner must provide procedures to insure that ballast tanks are charged with sea water whenever possible.

Cathodic protection can be provided by one of two mechanisms. The oldest method (Sacrificial Anodes) is the use of metal ingots (andes) of a less noble metal than steel (zinc, aluminum, magnesium, etc.) being attached to the steel. The less noble material corrodes in lieu of the steel . In reality, the anode provides an excess amount of electrons to the steel which can be lost to the electrolyte without conversion of the steel to a positive ion resulting in rust. The newer impressed current system provides excess electrons to the steel via some other electromotive device such as a battery or direct current rectifier. In this case, a metal alloy anode is made positive in relation to the steel to Which it is attached. As long as the power source operates the steel is protected.

Because no case histories could be found using the impressed current systems in ballast tanks, it was not considered in this report. In addition, two potentially hazardous problems can be created with impressed current systems. If not properly regulated, either chlorine or hydrogen gas can be liberated from the sea water. Chlorine gas is extrmely toxic, and explosive hydrogen gas can be extremely hazardous in confined areas.

At one time magnesium anodes were the preferred anode material for tanks but use was discontinued due to rapid anode depletion, high cost and high driving potential. Zinc and aluminum alloy anodes have become the industry standards for cathodic protection of tanks.

As a general rule, catholic protection systems do not perform satisfactorily on overhead surfaces of tanks due to air pockets. These areas are then subject to severe corrosion. Another problem associated with the use of cathodic protection in salt water ballast tanks is created from the residual water and wet silt left on the tank bottoms after deballasting. This salt muck provides a path for steel corrosion but since the catholic protection system (anodes) is above the surface of the muck, no protection is afforded.

To rectify these problems, high performance coatings have been applied to the overhead surfaces to include 6″ to 24″ down each bulkhead and frame plus the tank bottoms to include 6″ to 24″ above the bottom. During ballast, the protective coating system protects the steel and supplements the cathodic protection system, thereby reducing anode consumption. During the dry cycle, the coatings protect the high corrosion areas.

The lack of compatibility between coatings and cathodic protection systems is another potential problem which must be considered. Hartley[22] and Munger, et a1[31] discuss these problems in detail. Any coating used in conjunctiom with cathodic protection must act as a good barrier exhibiting properties of low water absorption and low moisture vapor transfer rates. They must have high dielectric strength and good resistance to the alkaline environment created by the cathodic protection system at the steel/coating interface. In some cases, hydroxyl ions are created which can actually saponify the oil in some coating systems which is subsequently washed away as soap.

The American Bureau of Shipping is considering excluding tanks "protected" by catholic protection from the provisions in the Rules permitting reduced scantling (see Annex B). The reason stated for possible exclusion is the unsatisfactory anode performance because of the following:

- The ballast water may be fresh or brackish with insufficient electrolyte.
- The ballast tanks may be only partially filled and anodes are not submerged.
- The anodes may not be renewed when they are wasted.
- The armies may become coated with mud from muddy ballast water and become ineffective.

During the course of this study an inquiry was sent to the United States Coast Guard requesting guidance on the use of cathodic protection systems in ballast tanks. In a response received from the Coast Guard (Annex C), no prohibition was cited for ballast tanks but specific rules do apply for cargo tanks. Other regulatory agencies have requirements governing the use of cathodic protection systems. "U.S. Coast Guard Rules and Regulations for Tank Vessel",[39] 46CFR35. 01-25, should be consulted prior to installing cathodic protection systems.

There are conflicting reports concerning the performance of sacrificial anode systems in uncoated ballast tanks. The literature[4,6,27,33,34] cites examples of successful performance of from 4 to 7 years. Discussion with port engineers and ship owner corrosion engineers established a useful made system life as being 4 to 5 years when used without coatings and 7 to 10 years with coatings. Kurr[27] reported 9 year satisfactory performance in coated ballast tanks. The Society of Naval Architects and Marine Engineers T&R Report R-21, "Fundamentals of Cathodic Protection for Marine Service", states that sacrificial anode systems should be designed to be replaced in four years.

In conclusion, anode systems can be designed to protect steel from corrosion for at least four years in uncoated tanks and eight years in coated tanks. Certain procedural requirements must be met:

- Tank must be empty or full
- Salt water must be used as ballast
- Tanks without coatings must be "pressed-up" to eliminate air pockets.
- Anodes must be inspected and replaced when spent.
- Compatibility between coatings and cathodic protection must be established.
- Partial coating of tanks is recommended over bare tank application especially in wing tanks.

2.3.1.3 soft coatings plus Cathodic Protection

The primary advantage of soft coatings is ease of application and tolerance for poor surface preparation. There are many types of soft coatings the market. For the purposes of this discussion, soft coatings are those which, even though dry (cured), are still relatively soft. In comparson,alkyds, epoxies, inorganic Zincs, are considered hard coatings.

Some of these soft coatings are petroleum oils, some are animal oils, some are wax, some are vegetable oils and some are true curing matings. No soft coating performance histories could be found in the literature; however, manufacturers claim 3 to 10 year satisfactory service histories. One important point to remember is the wide variation of composition of these products. Before selecting a specific material, actual satisfactory historical performance data should be obtained.

Some of the reported problems with soft coatings are:

- Slipperiness of coating due to incomplete drying (can hinder tank inspections)
- Surface flammability and burnback
- Removal during ballasting operations resulting in oil slicks
- Difficulty of tank inspection (muck accumulation on coating obscures structure.)

While formulating this research project, the 023-1 panel made a decision to evaluate the performance of soft coatings in combination with sacrificial cathodic protection. This decision became one of the most important aspects of the project. As will be seen in the discussion of the laboratory test results, five of the six coatings tested failed due to incompatibility with the cathodic protection system. This fact can be better understood by recalling the discussion in section 2.3.1.2 concerning the alkaline conditions created at the steel surface. The oil in the oil based coatings probably saponified and washed away. In conclusion, extreme care must be exercised when selecting soft coatings for use with cathodic protection. Actual testing to include wet and dry cycling should be performed prior to actual material selection and use.

2.3.1.4 Preinstruction Primer Plus Cathodic Protection

Many shipyards automatically abrasive blast and prime structural steel prior to fabrication. This primer is normally removed and replaced by a high performance tank coating system. If the tank coating could he eliminated and the preconstruction primer left in place, many construction dollars could possibly be saved. Therefore, this approach was selected as a possible alternative for investigation. Sacrificial anodes were selected to provide the actual corrosion control mechanism. Inorganic zinc was selected as the preconstruction primer. Inorganic zinc primers provide the best shipbuilding handling and steel protection characteristics.

No performance histories could be located using primers plus cathodic protection; however, there are case histories using base steel and anodes. One major limiting factor of cathodic protection can be tank geometry. In these cases, primers could actually compliment the cathodic protection system by protecting overheads, bottoms, and snail pocket areas.

2.3.1.5 Summary

In conclusion, there are many ways in Which to protect steel salt water ballast tanks. The 023-1 panel has selected four possible methods for evaluation. Each of these methods have definite advantages and limitations. Prior to selecting a specific combination, these points plus the laboratory testing results and economic analysis should be reviewed in detail.

2.3.2 Tank Test Results

To verify the relative performance of each proposed alternate and the campatibilities between the catholic protection and coating systems, a laboratory test program was formulated and presented to the 023-1 panel for approval. Following modification and final approval, the test program was performed.

Three ballast tank assemblies (4′ X 4′ X 10′) were fabricated from 1/4″ A-36 steel plate and shapes. Each assembly consisted of three separate test tanks. (See Figure 2.1). Each tank was constructed to duplicate ship ballast tanks as concerns structure and configuration (See Figure 2.2). One side of each tank was of bolted construction to allow access for inspection.

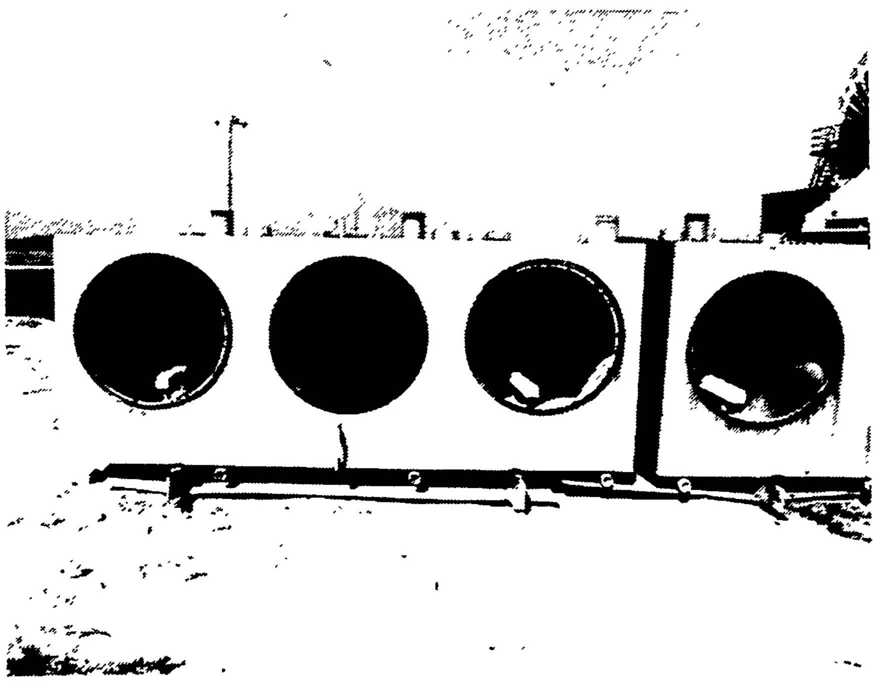


Figure 2.1: Photograph of One Test Tank Assembly

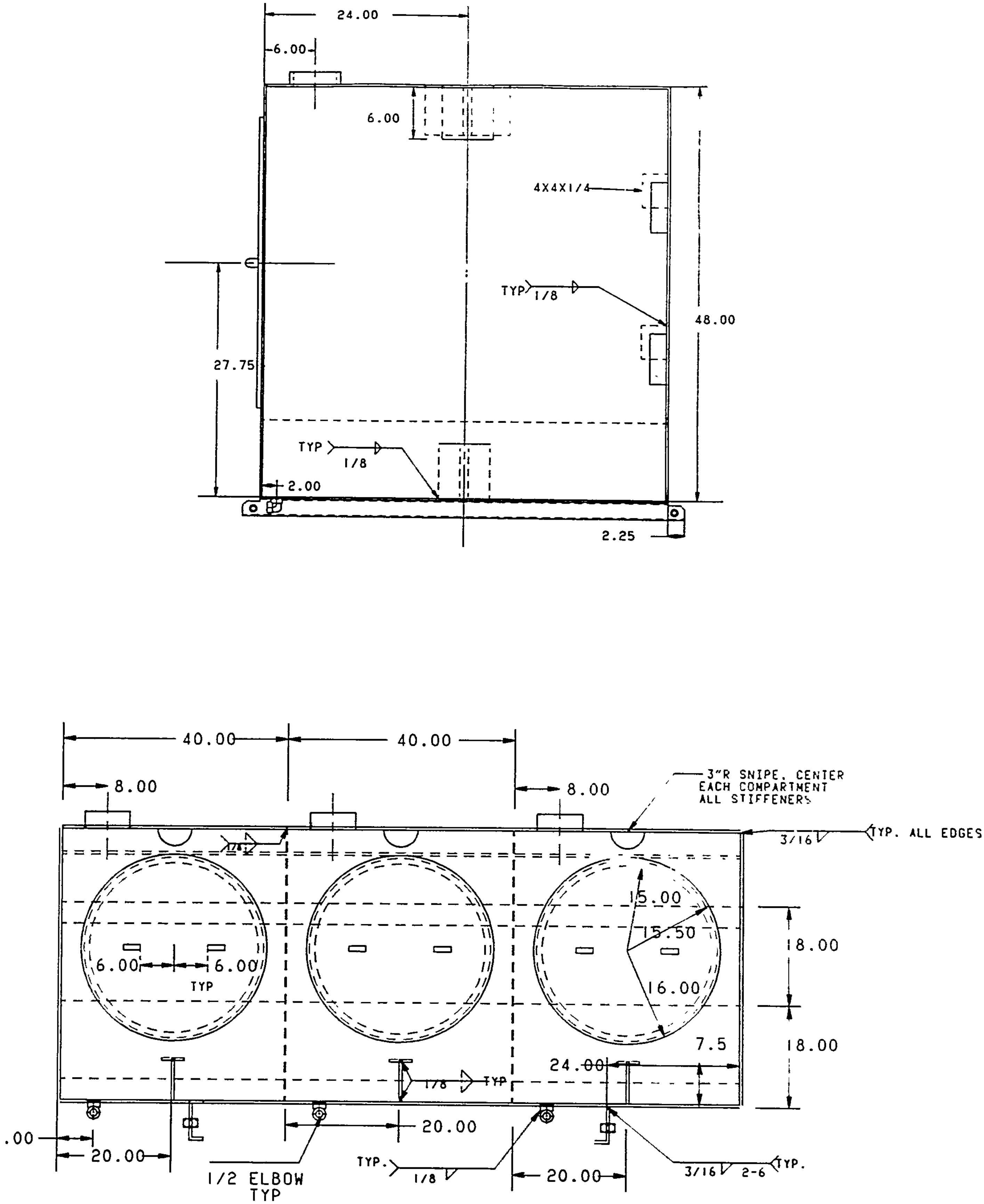


Figure 2.2: Drawing Showing Details of Test Tank Assembly

Table I contains information on each tank as to corrosion control alternate; i.e., surface preparation, coating system anode type, etc.

TABLE I

Corrosion Control Alternates Used In Tank Test

Tank Number	Surface Preparation	Coating System	Film Thickness (MILS)	Anode Type
1	SP10	Two Coat Epoxy (MIL-P-23236) Partially coated - Top plus 6" down bulkheads and Bottom plus 6" up bulkhead.	6 - 10	Aluminum Alloy (Galvalum III)
2	SP10	Two Coat Epoxy (MIL-P-23236) completely coated	6.5 - 8.5	None
3	SP10	Same as Tank 1	6 - 9.5	Zinc (MIL-A-18001H)
4	SP10	Inorganic zinc preconstruction primer applied prior to fabrication	2.0	Aluminum (Galvalum III)
5	SP10	Same as Tank 4	1.75 - 2.0	None
6	SP10	Same as Tank 4	1.8	Zinc (MIL-A-18001H)
7	Descaled prior to fabrication then allowed to rust	Soft coating (wax / oil)	7.0	Aluminum (Galvalum III)
8	Same as Tank 7	Same as Tank 7	7.0	None
9	Same as Tank 7	Same as Tank 7	7.0	Zinc (MIL-A-18001H)

Following tank fabrication and application/installation of each alternate, the tanks were ballasted and deballasted with fresh sea water. Table II contains data on the sea water used.

TABLE II

Test Site Sea Water Information
Water Resistivity ranged from 26 to 29 ohms/cm

	SPRING			SUMMER			FALL			WINTER		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Water Temperature (^{o}C)	17.0	20.0	18.6	26.5	30.0	28.3	17.0	30.5	23.8	14.5	25.0	18.2
pH	6.5	7.5	7.0	7.6	8.3	7.9	6.7	8.1	7.6	7.2	8.2	7.7
Oxygen (Dissolved)	5.8	8.5	6.8	4.2	7.8	5.9	4.2	7.6	5.4	5.2	9.4	6.5
Salinity (parts per 1000)	17.5	29.0	24.1	21.5	35.5	27.5	6.0	33.0	15.8	8.5	27.0	20.6

Each ballast cycle consisted of 20 days full and 10 days empty. Records were kept on sea water resistivity and cathodic protection half cell potentials. A copper/copper sulfate half cell was used for all potential measurements (see Table III).

TABLE III

Half Cell Potentials ($Cu/CuSO_4$)
(All Potentials Are Negative)

Tank	FIRST CYCLE					SECOND	THIRD	FIFTH	EIGHTH	TWELFTH
Number	Immediate	1HR	24HR	72HR	10DAYS	CYCLE	CYCLE	CYCLE	CYCLE	CYCLE
1	0.74	0.77	1.01	1.02	1.02	1.05	1.03	1.03	1.04	1.05
2	0.97	0.96	0.98	0.98	0.96	0.96	0.92	0.85	0.67	0.57
3	0.75	0.80	0.98	0.99	0.97	1.01	0.96	0.90	1.02	0.94
4	0.95	0.99	1.07	1.07	1.10	1.09	1.05	1.06	1.06	1.01
5	0.92	0.95	0.96	0.93	0.86	0.71	0.69	0.71	0.70	0.65
6	0.92	0.97	0.99	1.00	1.02	1.02	0.97	0.96	0.98	0.90
7	0.80	0.89	1.04	1.04	1.05	1.04	0.98	Discontinued due to complete cathodic protection induced coatings failure		
8	0.35	0.40	0.56	0.62	0.68	0.72	0.61			
9	0.85	0.90	0.98	1.00	0.99	1.00	0.92			

2.3.2.1 Performance of Tank 1 - Aluminum Anode with Partial Coatings

At the completion of the twelfth cycle, the entire uncoated area was rust colored. Removal of the calcareous deposit showed rust under the deposits. Where the deposit had delaminated, the area left exposed had rusted. See Figure 2.3. The aluminun anode was still providing sufficient potential to protect the steel (-1.05V); however, the calcareous deposit which had formed during the first and second cycle had loosened from the steel substrate and was apparently, in some manner, masking the anode. It was also noted early in the experiment that the deposit formed by the aluminum anode was more coarse and less tenacious than the zinc produced deposit. No significant amount of steel was lost in tank 1. Even though the steel was corroding, no significant amount of rust scale was present. Most of the rust was moderate to light.

2.3.2.2 Performance of Tank 2 - High Performance Coatings

Figure 2.4 is a graphic representation of the performance in Tank 2 at the end of twelve months. Tha main failure points were in the weld areas except for one small area on the right bulkhead. The judged amount of failure was 1%. Note that the half cell potential dropped from -O. 85V to -O. 67V between the fifth and eighth cycle and then to -0.57V at the end of the twelfth cycle. This corresponds to the beginning of coating failure. Even though the failure is not significant, it is significant that the measurements noted the beginning of failure.

2.3.2.3 Performance of Tank 3 - Zinc Anode with Partial Coatings

The color of the tank was primarily the color of the calcareous deposit. (See Figure 2.5). Removal of the deposit revealed tight black oxide under the film. Where the deposit had been removed, a new deposit had formed.

The calcareous deposit in Tank 3 took longer to form but was much more dense and tenacious than that formed with the aluminum anode.

2.3.2.4 Performance of Tank 4 - Preinstruction Zinc Primer plus Aluminum Anode

Early in the test cycle, the aluminum anode protected the zinc coating and even built up a calcareous deposit on bare welds and other damged areas. At the end of the last cycle, some of the calcareous coating remained but most was gone. The low primer milage areas (damaged

Figure 2.3: Photographs of Aluminum Anode/Partial Coatings at One Year

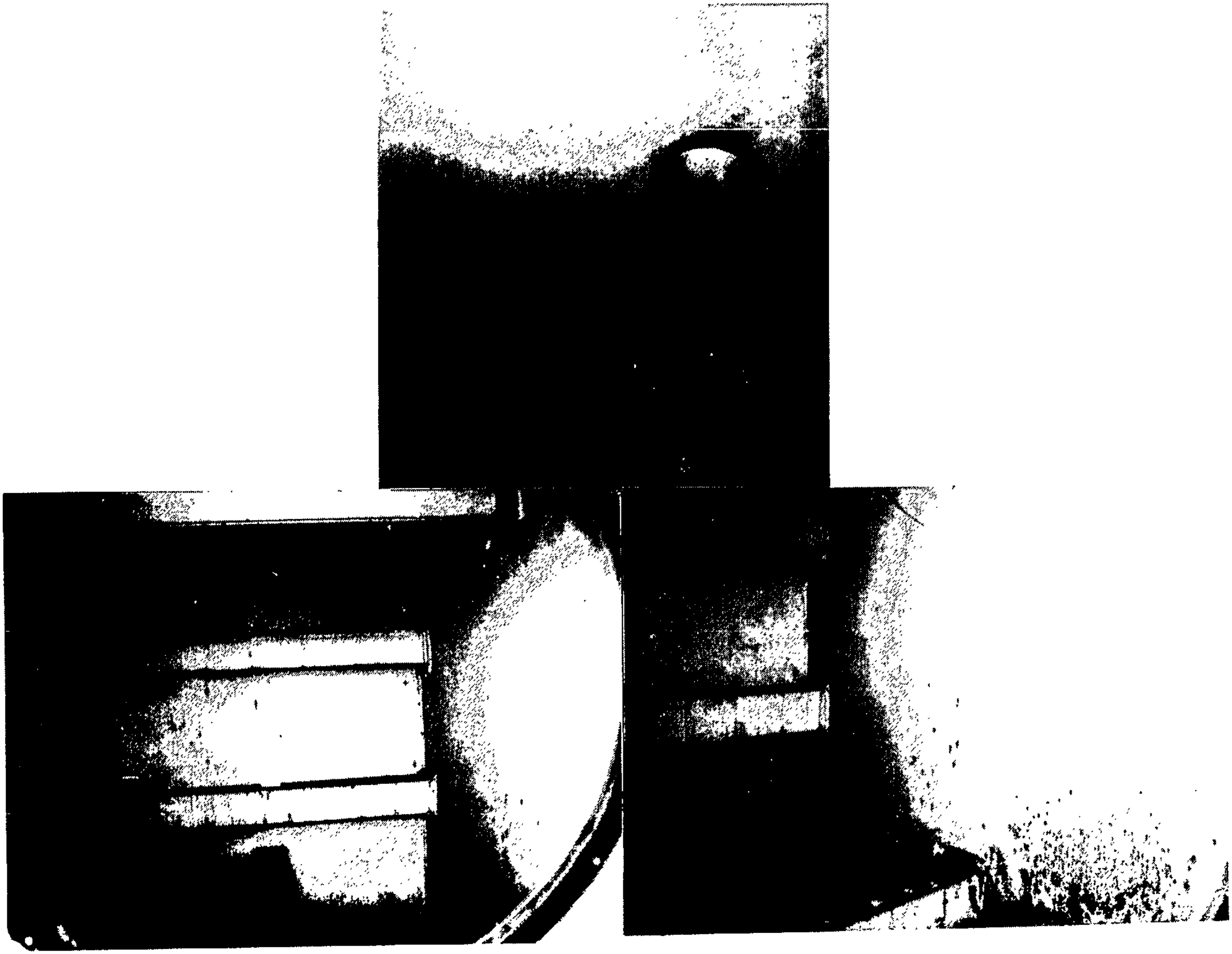


Figure 2.4: Photographs of High Performance Coatings at One Year

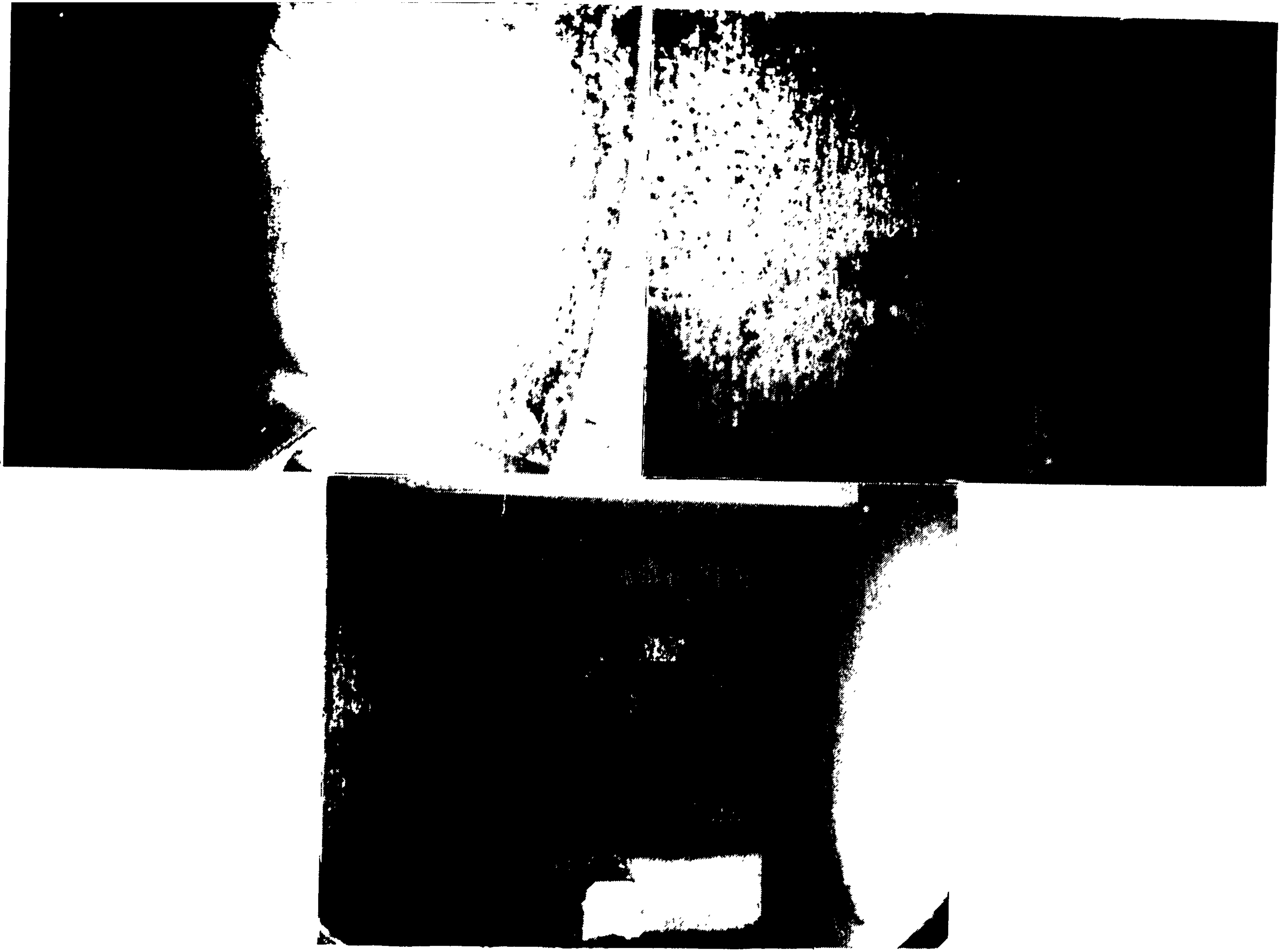


Figure 2.5: Photograph of Zinc Anode/Partial Coatings at One Year

during fabrication) were also beginning to show rust. The inorganic zinc coating was being depleted. See Figure 2.6. The measured anode potential was still sufficient to protect the steel.

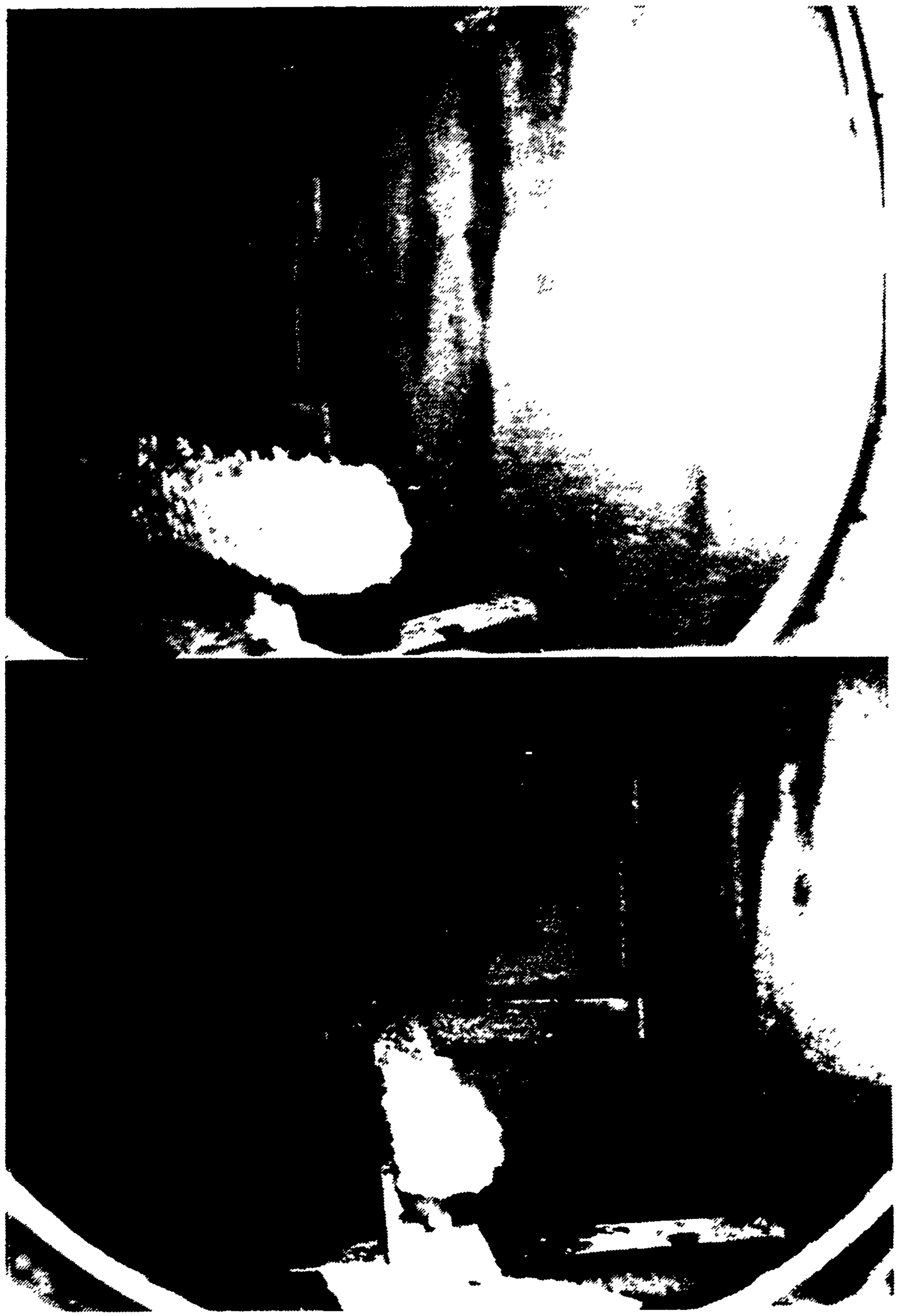


Figure 2.6: Photograph of Zinc Primer/Aluminum Anode at One Year

2.3.2.5 Performance of Tank 5 - Preconstruction Primer Only

Initially, a calcareous deposit was formed on welds and damaged areas; however, with time this deposit disappeared (approximate 9 months). At the end of the last cycle, all of the zinc Primer was used up and the steel was just beginning to rust. (See Figure 2.7).

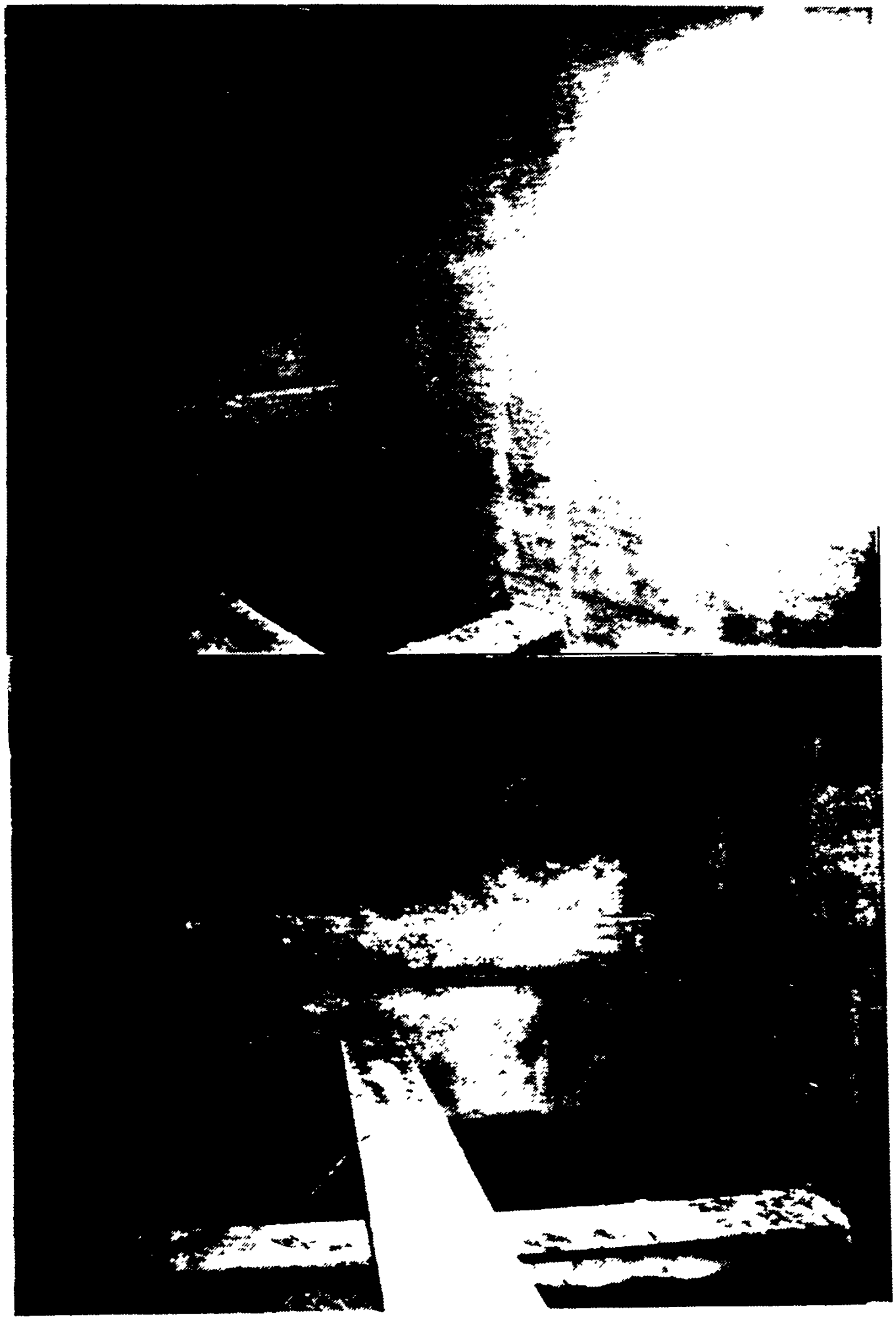


Figure 2.7: Photograph of Preconstruction Primer Only at One Year

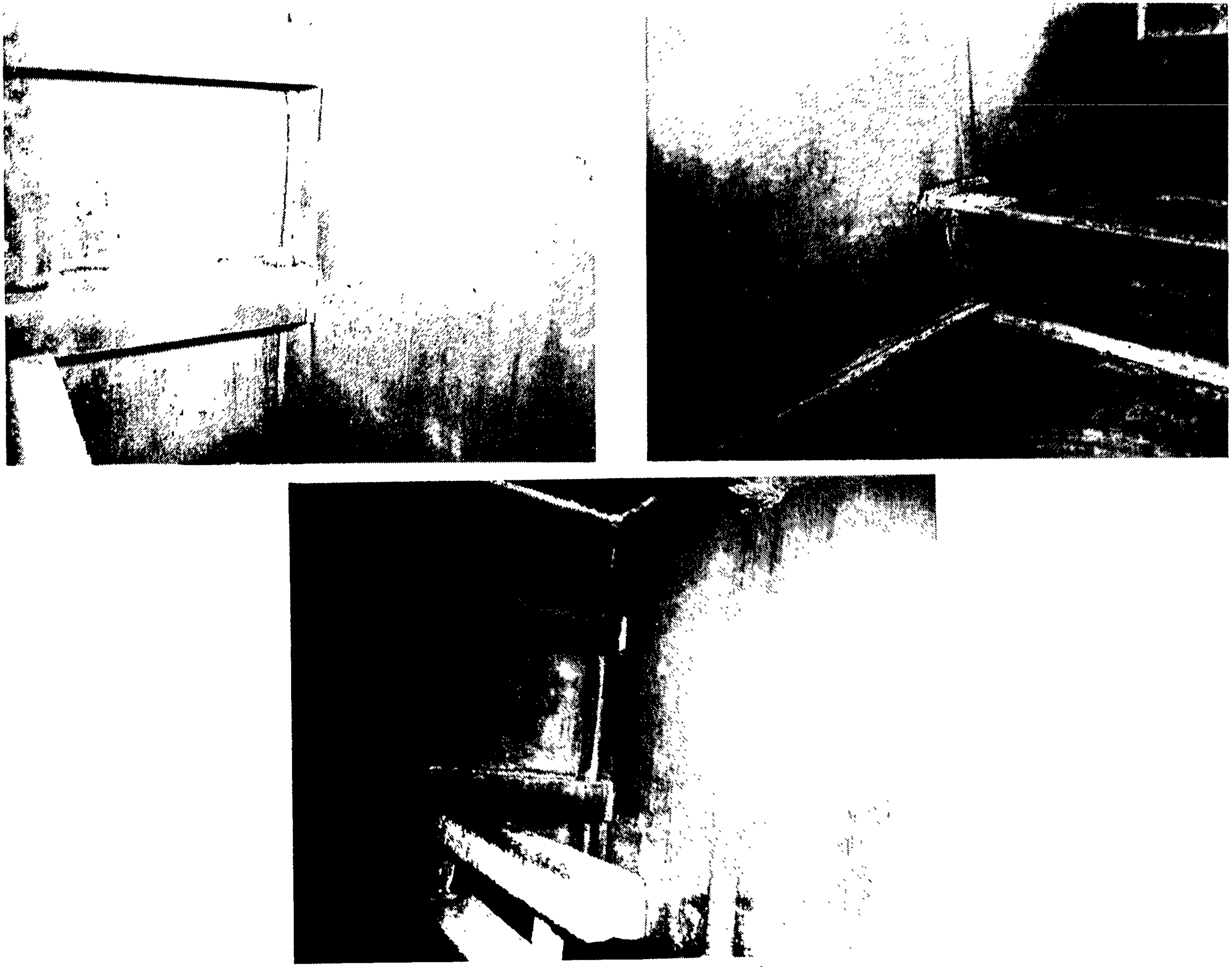


Figure 2.8: Photograph of Preconstruction Primer/Zinc Anode at One Year

2.3.2.6 Performance of Tank 6 - Preconstruction Primer Plus Zinc Anode

This was probably the best performing system tested. A calcareous deposit formed on all the surfaces after the second cycle. These deposits were still present at the conclusion of the test. Figure 2.8 are photographs of the system at the end of twelve months. Note the deposits on the weld area. Figure 2.9 is a graphic photograph of the accelerated corrosion in an air pocket at the top of the tank. This demonstrates the importance of “pressing-up” ballast tanks.

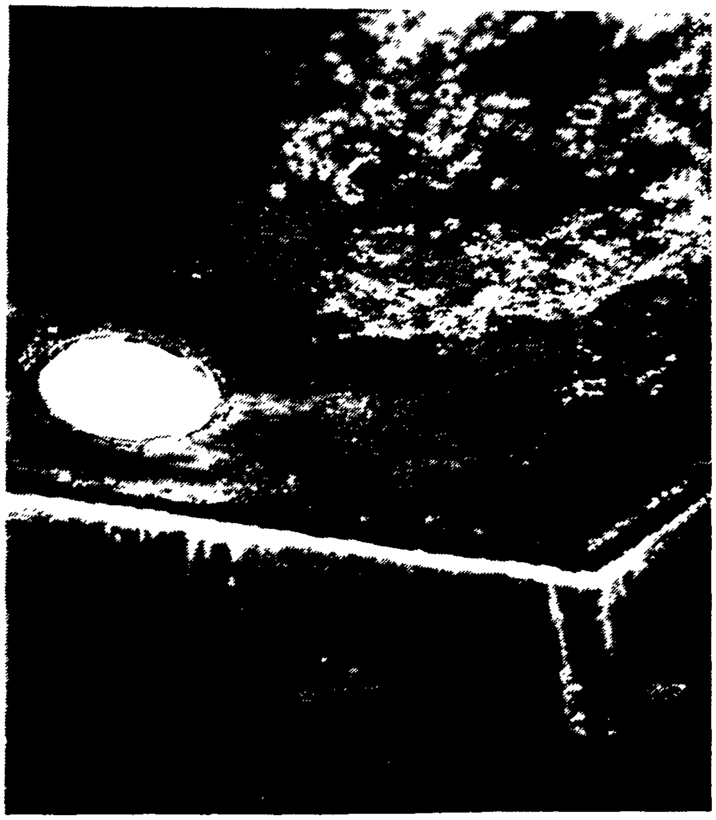


Figure 2.9: Photograph of Air Pocket Crrosion

2.3.2.7 Performance of Tanks 7, 8 and 9 - Soft Coatings With and Without Cathodic Protection

This part of the test was discontinued after two cycles because of the complete failure of the coating system when used with cathodic protection. Following failure of the coating, a screening test was initiated to select a new soft coating for use in the tanks. The second attempt also resulted in a major failure after - cycles. Four new materials were then selected for additional testing. After two wet/dry cycles, one coaating completely failed, two were marginal and a fourth was satisfactory. By this time it was too late to reinitiate testing of the soft coating with cathodic protection in the large tanks. Figure 2.10 is a photograph of the last screening tests. The soft coating with no anodes used in the initial tank phase looked good at the end of the second cycle but was not continued because the primary purpose for the test was to verify compatibility between cathodic protection and coatings.

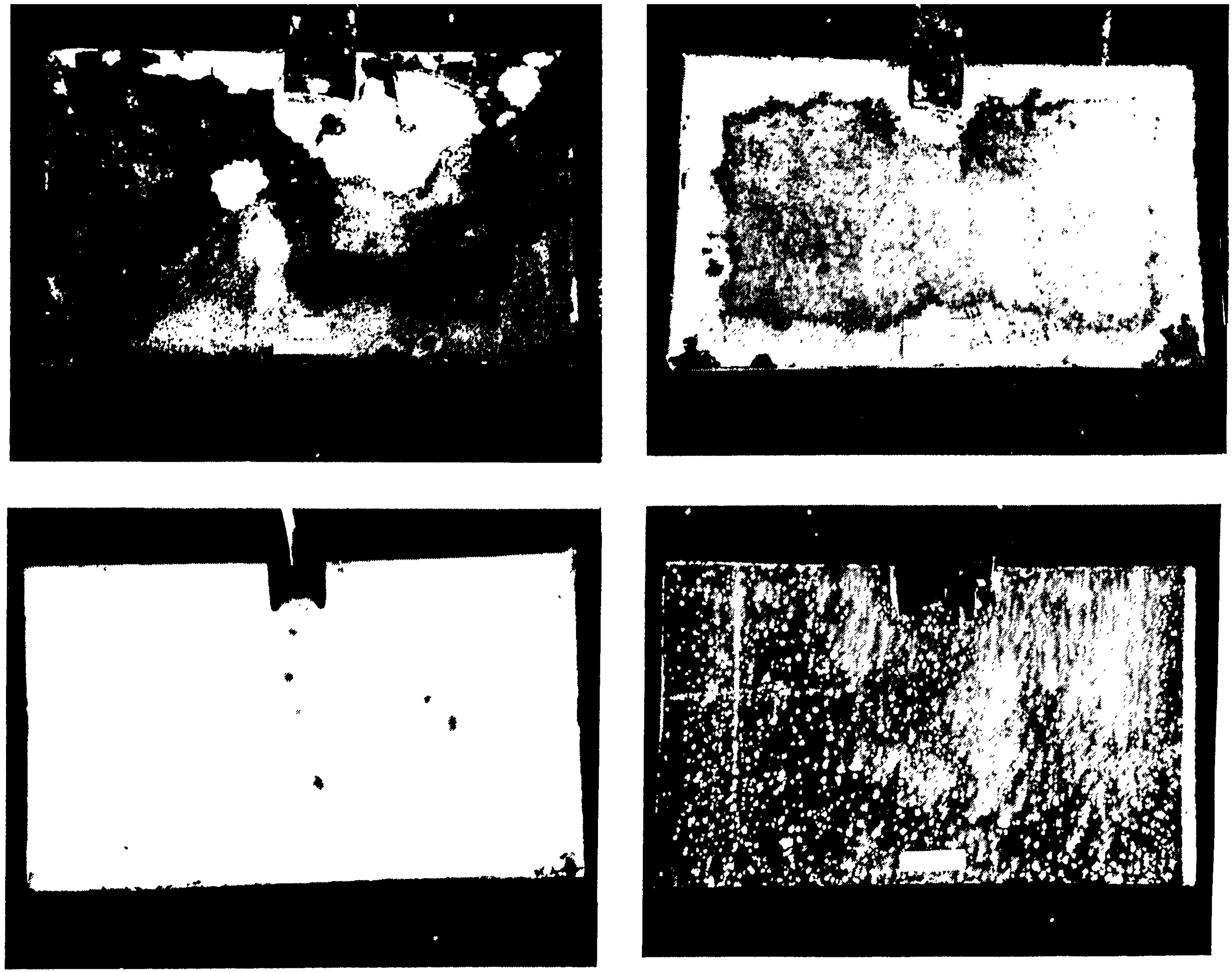


Figure 2.10: Soft Coatings Screening Results

2.3.3 Anode Performance

Prior to discussing actual anode performance, it is first necessary to know how anode requirements are calculated. Table IV lists the basic properties of the anodes used. In addition, two other facts must be known. The first is the required current density to protect the steel in the intended service.

TABLE IV

Basic Properties of Anodes in Sea Water

Anode Type	Current Capacity (Amp-hr/lb)	Consumption Rate (lb/Amp-Yr)	Potential
Zinc (MIL-A-1800m),	372	23	-1.01
Aluminum (Galvalum III)	1150	7.6	-1.08

For segregated ballast 14 milliamperes per ft^2 for uncoated areas and 1 milliamp for coated areas are the generally accepted values. The second is the sea water resistance which for the test was 26 to 29 ohms. The SNAME T&R Report R-21[6], "Fundamentals of Cathodic Protection for Marine Service" contains an equation which can be used to calculate required anode weights. This equation is listed below:

Equation 1:

$$W = \frac{A \times D \times F \times Y \times 8760}{I \times S \times 1000}$$

Where:
- A = Surface area to be protected in ft^2
- D = Required current density
- F = Factor which represents percent immersion the as a decimal
- Y = Design life in years (Usually 4)
- I = Anode Current Capacity (Amp-hr/lb)
- S = System Efficiency (Normally 85%)
- 8760 represents the number of hours in a year

This equation gives the actual total weight of required anodes; however, a minimum number of anodes must also be calculated based on anode current output. Anode current output can be calculated as outlined in the following paragraphs.

Generally anodes are designed to have a small cross section in relation to their length. The resistance of a slender rod anode in an electrolyte can be obtained from the following formula:

Equation 2:

$$R = \frac{P}{2\pi L}\left(\log_e \frac{2L}{r} - 1\right)$$

Where: R = Resistance in ohms

r = Mean effective radius of the anode in an (normally calculated at 40% consumption)

P = Resistivity of water in ohms an (26 ohms used for report calculation)

L = Length of the anode in ons.

Once the internal resistance of the anode has been calculated, the circuit voltage potential can also be determined by subtracting the potential of polarized steel from the anode potential. By knowing the internal circuit resistance (R) and the circuit potential (E), the current output of the anode (I) can be calculated from Ohms law:

Equation 3:

$$I = \frac{E}{R}$$

The minimum number of anodes can now be calculated:

Equation 4:

$$N = \frac{D \times A}{1000 \times I}$$

where: N = minimum number of anodes

D = Required current density

A = Surface area to be protected

I = Anode current output

The following examples will help understand the formulas required for anode determinations.

Tank 1 - Aluminum Anode with Partial Coatings

Surface Area Coated = 63 square feet
Surface Area Unmated = 46 square feet
Required Current Density
Coated Area = 1 milliamp/ft^2
Uncoated Area = 14 milliamps/ft^2
Immersion Factor = 0.6 (60% Ballast Time)
Design Life in Years = 4
System Efficiency = 0.85 (85% efficient)
Anode Current Capacity = 1150 Amp-hr/lb (from Table IV)

From Equation 1 the required anode weight can be calculated:

$$W_T = W_c + W_n$$

where: W_T = Total weight

W_c = Weight required for coated area

W_u = Weight required for uncoated area.

$$W_c = \frac{63\ ft^2 \times 1\ milliamp/ft^2 \times 0.6 \times 4\ Yr \times 8760\ hrs/yr}{1150\ Amp\text{-}hr/lb \times 1000\ milliamps/amp \times 0.85}$$

$$Wc = 1.35\ lbs$$

$$W_u = \frac{46\ ft^2 \times 14\ milliamps/ft^2 \times 0.6 \times 4\ Yr \times 8760\ hrs/yr}{1150\ Amp\text{-}hr/lb \times 1000\ milliamps/Amp \times 0.85}$$

$$W_u = 13.85\ lbs$$

$$W_T = 1.35\ lbs + 13.85\ lbs = \underline{15.2\ lbs}$$

Actual anode selected for test was a Stock 20 lb anode.

From equations 2, 3 and 4 the minimum number of anodes based on current capacity can be calculated:

Aluminum anode size was 2 1/2″ (6.35 cm) X 2 1/2″ (6.35 cm) X 30″ (76.2 cm)

Equation 2:

$$R = \frac{P}{2\pi L}\left(\log_e \frac{2L}{r} - 1\right)$$

where: L = 76.2 an

P = 26 ohms/cm

r can be calculated from

$$r = \frac{\text{Cross Section Area}}{\pi} \times .6 \text{ (40\% wasted anode)}$$

$$r = \frac{6.35 \text{ cm} \times 6.35 \text{ cm}}{\pi} \times .6$$

$$r = 7.7 \text{ cm}^2$$

substituting values into equation 2 gives:

$$R = \frac{26 \text{ ohm/cm}}{2\pi(76.2 \text{ cm})}\left(\log_e \frac{2 \times 76.2 \text{ cm}}{7.7 \text{ cm}} -1\right)$$

R = 0.16 ohms

E can be obtained by subtracting the potential of polarized steel from the aluminum anode potential:

$$\begin{array}{r} 1.08 \text{ volts} \\ - \ 0.80 \text{ volts} \\ \hline 0.28 \text{ volts} \end{array}$$

Therefore:

$$\text{Current Output (I)} = \frac{0.28}{0.16}$$

$$I = 1.75 \text{ amps}$$

Now using Equation 4 the minimum number of anodes can be calculated:

$$N = \frac{D \times A}{1000 \times I}$$

$$N = \frac{14 \text{ milliamps/ft}^2 \times 46\text{ft}^2}{1000 \text{ milliamp/amp} \times 1.75 \text{ amps}}$$

N = 0.37 or rounding up to nearest whole number

$N = 1$

These same formulas can be used to calculate the number of anodes (zinc and/or aluminum) for large tanks. The actual placement of the anodes requires the services of an engineer trained in cathodic protection and should not be attempted by anyone else.

Tank 3 - zinc anode with partial coating

$$W_T = W_C + W_u$$

$$W_C = \frac{63 \text{ ft}^2 \times 1 \text{ milliamp/ft}^2 \times 0.6 \times 4 \text{ yr} \times 8760 \text{ hrS/yr}}{372 \text{ Amp-hr/lb} \times 1000 \text{ milliamps/Amp} \times 0.85}$$

W_C = 4.19 lbs

NOTE: The only difference between this calculation and the one for aluminum is the anode current capacity (372 versus 1150).

$$W_u = \frac{46 \text{ ft}^2 \times 14 \text{ milliamps/ft}^2 \times 0.6 \times 4 \text{ yr} \times 8760 \text{ hrS/yr}}{372 \text{ Amp-hr/lb} \times 1000 \text{ milliamp/Amp} \times 0.85}$$

W_u = 42.82 lbs

W_T = 4.19 + 42.82 = 47.01 lbs

One standard 50 lb anode was selected

The minimum number of anodes based on anode current capacity also calculates as one anode required.

Now that the total anode requirement for each tank has been calculated, the same equation can be used to calculate pro jected annual anode consumption. This data can be compared to the actual measured weight loss of each anode used in the laboratory test place.

Table V lists the calculated theoretical projected anode consumption rates for each tank plus the actual weight loss for each tank tested.

TABLE V

Anode Performance Summary (12 months)

Tank Number	Anode Type	Theoretical Weight Loss at 100% Efficiency (lbs)	Actual Weight Loss (lbs)	Actual Effici (%)
1	Aluminum (Galvalum III)	3.23	2.55	127%
3	Zinc (MIL-A-19001H)	10.00	4.36	229%
4	Aluminum (Galvalum III)	1.44*	1.17	123%
6	Zinc (MTL-A-18001H)	4.47*	1.52	294%
7	Aluminum (Galvalum III)	Test Discontinued	0.51**	
9	Zinc (MIL-A-18001H)	Test Discontinued	0.65**	--

*Assumes 15% damaged area.

**2 months only.

Three conclusions can be drawn from the results contained in Table V. First is that all anodes performed at better than 100% efficiency; second, the zinc anodes outperformed the aluminum anodes, and third, the tank with zinc anodes and inorganic zinc preconstruction primer performed the best of all systems tested.

One probable explanation of the increased anode efficiency was the calcareous deposits formed on bare areas. Once formal, the anode demand decreased, therefore slowing consumption. Because the zinc anode created a calcareous deposit which was more dense and tenacious, less of the deposit was removed during ballastimg. Again, reduced bare areas reduced anode consumption. Zinc anodes are also reported in the literature as being more dependable and reliable than aluminum anodes.[27]

In the tank with inorganic zinc preconstrution primer, no detectable amount of zinc primer was depleted during the test with the exception of the are within an air pocket at the top of the tank. The weight loss of the zinc anode was such that the system would theoretically continue to protect for twenty years with no anode replacement. The aluminum anode in the zinc primed tank probably exceeded the calculated theoretical consumption rate because the aluminum was actually depleting to protect the zinc which was at a lower potential. It is certainly within the realm of possibility that the zinc anode system would last for eight years as opposed to the normal four year life.

Figure 2.11 is a close-up photographs of each anode after cleaning. Figure 2.12 are photographs showing the relative wastage of each anode tested. Tank 1 through 9 start at the right or top of the photographs.

In summary, the zinc anodes outperformed the aluminum anodes for the given test conditions. In all cases, the anodes performed better than the 85 percent projected efficiency.

2.3.4 Economic Analysis

2.3.4.1 Initial Construction Assumptions

Ihe ship used as a model in this analysis was a 40,000 gross ton ship. The ballast tank surface area was assumed to be 150,000 total square feet. The detail manufacturing process varied with the corrosion control alternate; however, all steel shapes and plates were initially automatically abrasive blasted to remove mill scale. In the case of the preconstruction primer, this was applied by automatic means immediately following prefabrication blasting.

The first coat of the epoxy tank coating was applied in the subassembly configuration. The final coat of epoxy was applied after tank test. The soft coatings were applied after tank test. In all cases, the anodes were installed after all coatings applications were complete. These same procedures were followed for the tank coatings test program.

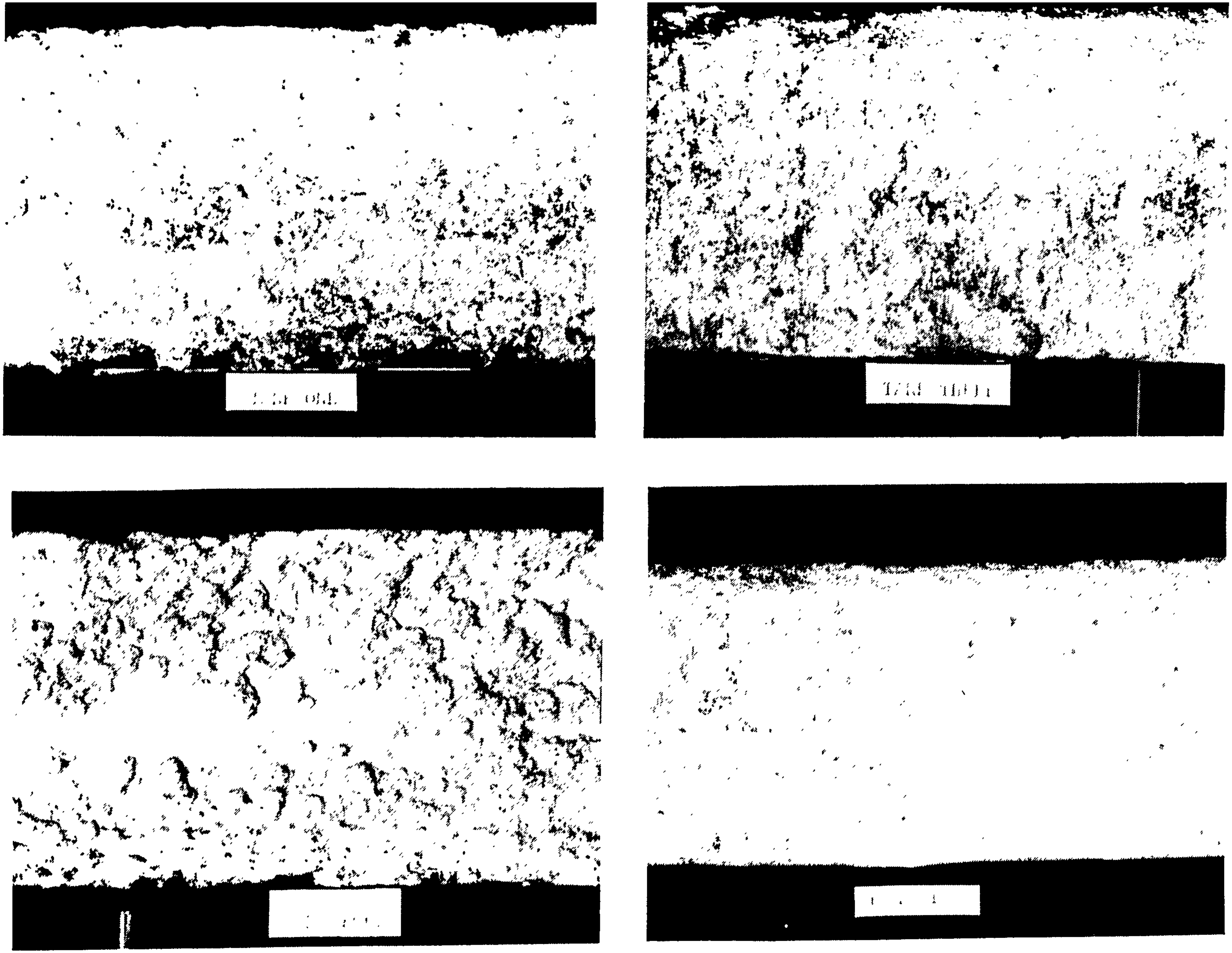
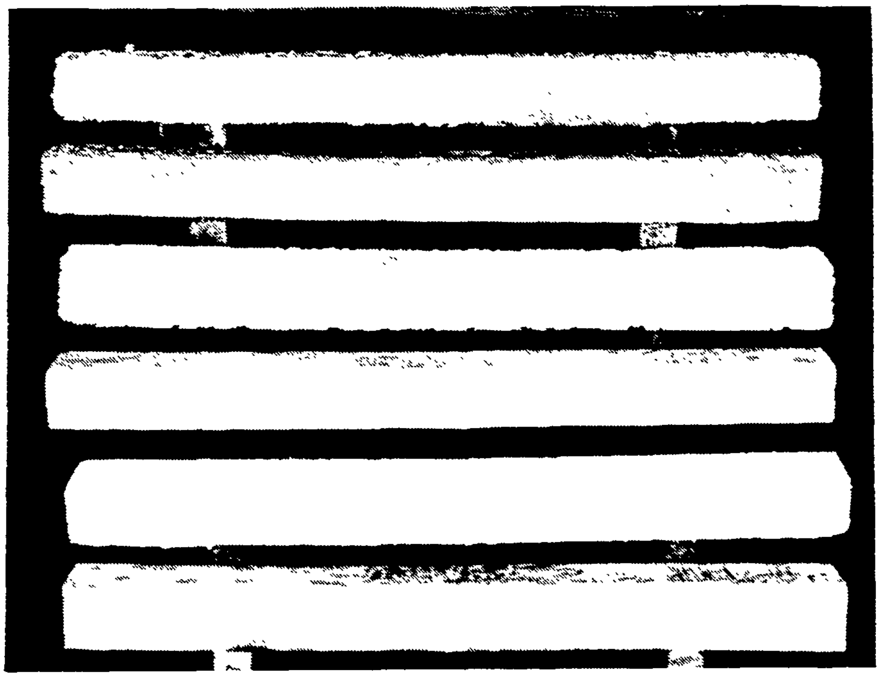


Figure 2.11: Close-up Photographs of Anodes After One Year



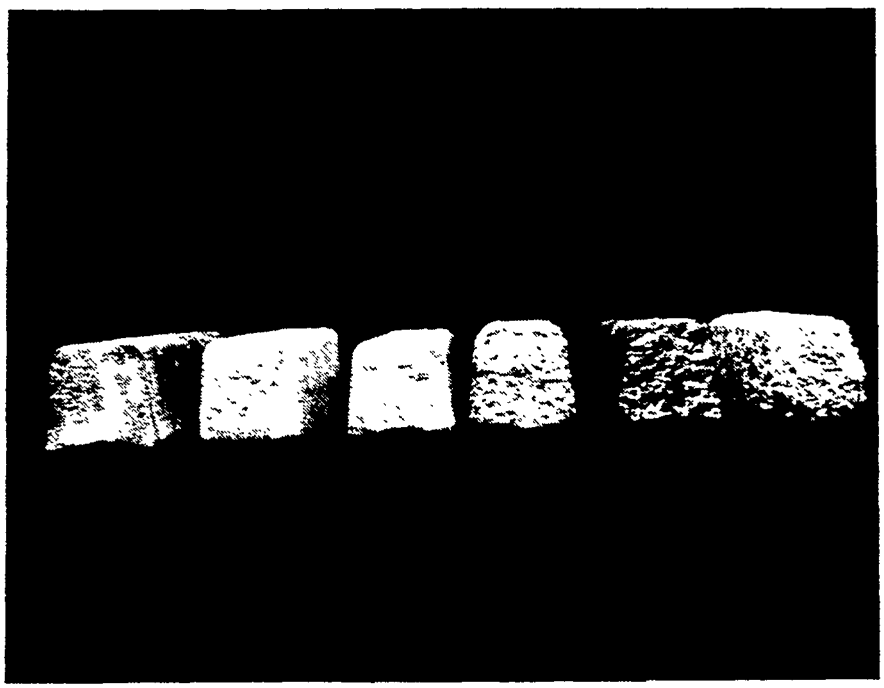


Figure 2.12: Comparison Photograph of Anodes After One Year

2.3.4.2 High Performance Coatings Assummptions

Complete coating of ballast tanks with high performance coatings is an industry standard and is therefore the baseline approach for the economic analysis. Two cases were assumed for the high performance coating system. These cases are based on actual corrosion control plans from two different ship owners.

The first plan consists of initially painting of the entire tank surface area with an epoxy tank coating system during the shipbuilding cycle. NO maintenance is performed on the coating for ten years unless a major paint failure occurs. At the end of ten years, the entire coating system is removed and replaced. In the economic analysis, the primary case considered was renewal at 10 years; however, a sensitivity analysis was performed to show cost impact with renewal at eight years.

The second plan consists of initial coatings application as outlined in the first plan. The primary difference in this plan is that the shipowner maintains the coating at 5 year intervals with 2% replacement during the first five years, 5% replacement during the second five years (10 year total) and complete renewal at 15 years.

2.3.4.3 Partial Coatings with Cathodic Protection

In this case, the uncoated area was assumed to be 50% of the total surface area (75,000 sq. ft.). Using the equations contained in section 2.3.3, the calculated anode requirement was 1500 zinc anodes or 810 aluminum anodes. Ihe ballast tanks were ballasted full 60% of the time. The anode requirement was calculated based on renewal at 4 year intervals. However, based on the test results and case histories, the replacement cycle was extended to eight years. The economic analysis considers both cases. No coatings are renewed during the twenty year life cycle.

2.3.4.4 Soft Coatings with Cathodic Protection

Following the initial descaling operation, the steel is allowed to rust during the manufacturing cycle. Just prior to coatings application, only loose rust and scale is removed. Anodes are installed after coatings.

Since no data could be found on how to calculate anode requirements, the laboratory test condition was selected. This condition equates to approximately 3.5 milliamps per square foot for eight years or 7 milliamps per square foot for four years. 1400 zinc or 750 aluminum anodes were required. Both cases were considered. Sixty percent ballast time and 10 percent coatings replacement at 4 year intervals were assumed.

2.3.4.5 Preconstruction Primer with Zinc Anodes

As stated above, the preconstruction primer was applied automatically prior to fabrication. No touch-up was performed during construction. The primer was assumed to be inorganic zinc. The amout of damaged area was assumed to be 15 percent of the total surface area. Calculated anode requirements were based on 14 milliamps per square foot for damaged/bare areas and 1 milliamp per square foot for primed areas. The total anode requirement was 1400 zinc anodes. Sixty percent ballast time was assured. No aluminum anodes were considered because of the results of the tank test program. Four and eight year anode replacement cycles were analyzed. The probable case was 8 plus years based on the test results. No matings are to be replaced during the life cycle.

2.3.4.6 General Assumptions

The following general assumptions were made:

- Twenty year economic ship life
- Escalation rate of 8 percent per year
- Salvage value of ship not affected by protection system
- Anodes were priced at $35.00 each
- High performance coating was priced at $25.00 per gallon with a coverage of 100 ft^2 per gallon
- Preconstruction primer (inorganic zinc) was priced at $25.00 per gallon with a coverage of 300 ft^2 per gallon
- Soft coating was priced at $10.00 per gallon with a coverage of 65 ft^2 per gallon
- Blasting material was priced at $15.00 per 200 ft^2 of surface area
- Initial installation of anodes was 1 manhour each
- At drydocking, installation of anodes was 1.5 manhours each

- o Staging, ventilation and miscellaneous services was based on rate of 10% of blast, paint and anode installation manhours
- o Rates for drydocking were approximately $0.50 per gross weight tons per day
- o Rates for shore services was $500 per day
- o Rate for lost revenue was $8000 per day
- o Lost rate revenues were only considered in those cases (4A, 4B and 4c) where work could not be completed in the normal 7 day out of service period.

2.3.4.7 Explanation of Economic Analysis Method

The cases were evaluated using Present Worth After Taxes (PWAT) as a measure of life cycle costs. Cases with lower FWAT are economically more desirable than cases with higher FWAT.

The analysis was developed using the Discounted Cash Flow (DCF) method. For each case, an estimate was made for the each flow in each year for the 20 year life of the vessel. The values for each year were tabulated and added. (Years with zero cash flow are not shown.) Adjustments were made for tax savings due to depreciation and investment tax credit. A 46% Federal Income Tax rate was assumed and a 10% investment tax credit was used. Depreciation was based on the Accelerate Cost Recovery System (ACRS) for 5 year property placed in service between 1981 and 1984. Net cash flows in each year were discounted to the first year using a 12% discount rate. (The first year was not discounted.) The discounted values were then algebraically summed to arrive at the PWAT for each case.

2.3.4.8 Results of Analysis

The computer printouts at the end of this section contain the results of each economic case. As can be seen, sensitivity analyses have been performed on some data to show impact. Tables VI and VII contain summaries of the analysis.

TABLE VI

Summary of Economic Analysis

Alternate	Case No.	Coating Replacement (YRS)	Anode Replacement (YRS)	Cost ($) First Year	Cost ($) Twentieth Year (Total)
High Performance Coatings - No Maintenance	4A	8	NONE	408,852	1,319,974
High Performance* Coatings - No Maintenance	4B	10	NONE	408,852	654,020
High Performance* Coatings - With Maintenance	4C	15	NONE	408,852	824,653
Partial Coatings Zinc Anodes	1A	NONE	4	376,443	724,142
Partial Coatings Aluminum Anode	1B	NONE	4	321,597	514,923
Partial Coatings* Zinc Anodes	1C	NONE	8	376,443	465,415
Partial Coatings Aluminum Anodes	1D	NONE	8	321,597	349,539
Soft Coatings Zinc Anodes	3A	10% at 4 YR INTERVALS	8	318,273	473,018
Soft Coatings Aluminum Anodes	3B	10% at 4 YR INTERVALS	8	253,455	369,633
Soft Coatings Zinc Anodes	3C	10% at 4 YR INTERVALS	4	318,273	690,721
Soft Coatings Aluminum Anodes	3D	10% at 4 YR INTERVALS	4	253,455	515,293
Preconstruction* Primer - Zinc Anode	2A	NONE	8	258,441	377,944
Preconstruction Primer - Zinc Anode	2B	NONE	4	258,441	623,092

*Substantiated by historical and test data.

As can be seen from Table VI, the preconstruction primer with zinc anodes replaced at 8 year intervals (Case 2A) is the least expensive (proven) initial cost system. This is also the best system performer in the tank tests discussed in paragraph 2.3.2.6. The twentieth year cost is a little more expensive than the soft coating with cathodic protection; however, the soft coating with cathodic protection is a suspect system (note system failures in tank test). There is a substantial crest difference between the preconstruction primer system and the standard two coat epoxy systems. Taking a worst case, namely anode replacement at 4 year intervals, the preconstruction primer approach (Case 2B) is still less costly over twenty years than either complete coatings approach.

Partial coatings and cathodic protection with anode replacement at 8 years (Cases lC and lD) are also less costly than complete coatings systems. Even if the anode replacement cycle is reduced to 4 years (Cases IA and lB), the cost is comparable to completely coated tanks. If complete coating systems are replaced at intervals shorter than 10 years, such as shown in Case 4A, the partial coatings cathodic protection approach is even more cost effective.

In conclusion, the preconstruction primer and partial coatings systems supplemented with cathodic protection are viable, cost effective corrosion control alternatives for ballast tanks.

The soft coatings with cathodic protection are also attractive systems cost wise, but extreme care must be exercised prior to selecting such a system. As stated earlier, 5 out of 6 tested systems either failed or were marginal in a test environment.

TABLE VII

Listing of Proven Corrosion Control Alternatives in Ballast Tanks By Least Expensive Approach

Alternate	First Year (Initial)	Twentieth Year (Total)
Preconstruction Zinc Primer with zinc anodes replaced at 8 year intervals	$258,441	$377,944
Partial Coatings with zinc anodes replaced at 8 year intervals	$376,443	$465,415
High Performance Coating No maintenance replaced at 10 years	$408,852	$654,000
High Performance Coating with maintenance replaced at 15 years	$408,852	$824,653

CFCASE1A

PWAT/CASH FLOW ANAYSIS

PARTIAL COATING WITH CATHODIC PROTECTION - ZINC ANODES
ANODE REPLACEMENT AT 4 YEAR INTERVALS - NO COATING MAINTENANCE OR REPLACEMENT

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	293000									293000
Anode Installation	160000									160000
MAINTENANCE EXPENSE										
Anode Replacement	0	0	0	208000	0	283000	385000	524000	0	1400000
Coating Repairs	0	0	0	0	0	0	0	0	0	0
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	453000	0	0	208000	0	283000	385000	524000	0	1853000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	67950	99660	95130	95130	95130					453000
TAX SAVING @ 46%	-31257	-45844	-43760	-43760	-43760	0	0	0	0	-208381
INVESTMENT TAX CREDIT	-45300									-45300
NET CASH FLOW	376443	-45844	-43760	164240	-43760	283000	385000	524000	0	1599319
DISCOUNT RATE - % - 12										
DCF	376443	-40932	-34885	116902	-27810	128014	110678	95732	0	724142
CUMULATIVE PWAT	376443	335511	300626	417528	389718	517732	628410	724142	724142	724142

NOTES: Assumed escalation rate 8% per year.
Assumed economic life of ship 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

FWAT/CASH FLOW ANAYSIS

PARTIAL COATING WITH CATHODIC PROTECTION - ALUMINUM ANODES
ANODE REPLACEMENT AT 4 YEAR INTERVALS - NO COATING MAINTENANCE OR REPLACEMENT

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTA
CAPITAL										
Coating Installation	293000									29300
Anode Installation	94000									9400
MAINTENANCE EXPENSE										
Anode Replacement	0	0	0	133000	0	181000	246000	335000	0	89500
Coating Repairs	0	0	0	0	0	0	0	0	0	
LOST REVENUE	0	0	0	0	0	0	0	0	0	
CASH FLOW B/FIT	387000	0	0	133000	0	181000	246000	335000	0	128200
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	58050	85140	81270	81270	81270					38700
TAX SAVING @ 46%	-26703	-39164.4	-37384.2	-37384.2	-37384.2					-1780
INVESTMENT TAX CREDIT	-38700									-3870
NET CASH FLOW	321597	-39164.4	-37384.2	95615.8	-37384.2	181000	246000	335000	0	106528
DISCOUNT RATE (%) - 12										
DCF	321597	-34968	-29802	68057	-23758	81875	70719	61203	0	51492
CUMULATIVE FWAT	321597	286629	256827	324884	301126	383001	453720	514923	514923	51492

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE1C

PWAT/CASH FLOW ANAYSIS

PARTIAL COATING WITH CATHODIC PROTECTION - ZINC ANODES
ANODE REPLACEMENT AT 8 YEAR INTERVALS - NO COATING MAINTENANCE OR REPLACEMENT

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	293000									293000
Anode Installation	160000									160000
MAINTENANCE EXPENSE										
Anode Replacement	0	0	0	0	0	283000	0	524000	0	807000
Coating Repairs	0	0	0	0	0	0	0	0	0	0
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	453000	0	0	0	0	283000	0	524000	0	1260000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	67950	99660	95130	95130	95130					453000
TAX SAVING @ 46%	-31257	-45844	-43760	-43760	-43760	0	0	0	0	-208381
INVESTMENT TAX CREDIT	-45300									-45300
NET CASH FLOW	376443	-45844	-43760	-43760	-43760	283000	0	524000	0	1006319
DISCOUNT RATE - % - 12										
DCF	376443	-40932	-34885	-31147	-27810	128014	0	95732	0	465415
CUMULATIVE PWAT	376443	335511	300626	269479	241669	369683	369683	465415	465415	465415

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE1D

FWAT/CASH FLOW ANAYSIS

PARTIAL COATING WITH CATHODIC PROTECTION - ALUMINUM ANODES
ANODE REPLACEMENT AT 8 YEAR INTERVALS - NO COATING MAINTENANCE OR REPLACEMENT

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	293000									293000
Anode Installation	94000									94000
MAINTENANCE EXPENSE										
Anode Replacement	0	0	0	0	0	181000	0	335000	0	516000
Coating Repairs	0	0	0	0	0	0	0	0	0	0
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	387000	0	0	0	0	181000	0	335000	0	903000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	58050	85140	81270	81270	81270					387000
TAX SAVING @ 46%	-26703	-39164	-37384	-37384	-37384	0	0	0	0	-178019
INVESTMENT TAX CREDIT	-38700									-38700
NET CASH FLOW	321597	-39164	-37384	-37384	-37384	181000	0	335000	0	686281
DISCOUNT RATE - % - 12										
DCF	321597	-34967	-29802	-26609	-23758	81875	0	61203	0	349539
CUMULATIVE FWAT	321597	286630	256828	230219	206461	288336	288336	349539	349539	349539

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE2A

PWAT/CASH FLOW ANAYSIS

PRECONSTRUCTION PRIMER WITH CATHODIC PROTECTION - ZINC ANODES
ANODE REPLACEMENT AT 8 YEAR INTERVALS - NO COATING MAINTENANCE OR REPLACEMENT

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	161000									161000
Anode Installation	150000									150000
MAINTENANCE EXPENSE										
Anode Replacement		0	0	0	0	268000	0	497000	0	765000
Coating Repairs		0	0	0	0	0	0	0	0	0
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	311000	0	0	0	0	268000	0	497000	0	1076000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	46650	68420	65310	65310	65310					311000
TAX SAVING @ 46%	-21459	-31473	-30043	-30043	-30043	0	0	0	0	-143061
INVESTMENT TAX CREDIT	-31100									-31100
NET CASH FLOW	258441	-31473	-30043	-30043	-30043	268000	0	497000	0	901839
DISCOUNT RATE - % - 12										
DCF	258441	-28100	-23950	-21384	-19092	121229	0	90800	0	377944
CUMULATIVE PWAT	258441	230341	206391	185007	165915	287144	287144	377944	377944	377944

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE2B

PWAT/CASH FLOW ANAYSIS

PRECONSTRUCTION PRIMER WITH CATHODIC PROTECTION - ZINC ANODES
ANODE REPLACEMENT AT 4 YEAR INTERVALS - NO COATING MAINTENANCE OR REPLACEMENT

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	161000									161000
Anode Installation	150000									150000
MAINTENANCE EXPENSE										
Anode Replacement		0	0	197000	0	268000	365000	497000	0	1327000
Coating Repairs		0	0	0	0	0	0	0	0	0
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	311000	0	0	197000	0	268000	365000	497000	0	1638000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	46650	68420	65310	65310	65310					311000
TAX SAVING @ 46%	-21459	-31473	-30043	-30043	-30043	0	0	0	0	-143061
INVESTMENT TAX CREDIT	-31100									-31100
NET CASH FLOW	258441	-31473	-30043	166957	-30043	268000	365000	497000	0	1463839
DISCOUNT RATE - % - 12										
DCF	258441	-28100	-23950	118836	-19092	121229	104928	90800	0	623092
CUMULATIVE PWAT	258441	230341	206391	325227	306135	427364	532292	623092	623092	623092

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE3A

PWAT/CASH FLOW ANAYSIS

SOFT COATING WITH CATHODIC PROTECTION - ZINC ANODES
ANODE REPLACEMENT AT 8 YEAR INTERVALS - 10% SOFT COATING REPLACEMENT AT 4 YEAR INTERVALS

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	233000									233000
Anode Installation	150000									150000
MAINTENANCE EXPENSE										
Anode Replacement		0	0	0	0	238000	0	440000	0	678000
Coating Repairs		0	0	35000	0	47000	64000	88000	0	234000
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	383000	0	0	35000	0	285000	64000	528000	0	1295000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	57450	84260	80430	80430	80430					383000
TAX SAVING @ 46%	-26427	-38760	-36998	-36998	-36998	0	0	0	0	-176181
INVESTMENT TAX CREDIT	-38300									-38300
NET CASH FLOW	318273	-38760	-36998	-1998	-36998	285000	64000	528000	0	1080519
DISCOUNT RATE - % - 12										
DCF	318273	-34607	-29494	-1422	-23512	128919	18398	96463	0	0
CUMULATIVE PWAT	318273	283666	254172	252750	229238	358157	376555	473018	473018	473018

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE3B

PWAT/CASH FLOW ANAYSIS

SOFT COATING WITH CATHODIC PROTECTION - ALUMINUM ANODES
ANODE REPLACEMENT AT 8 YEAR INTERVALS - 10% SOFT COATING REPLACEMENT AT 4 YEAR INTERVALS

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	233000									233000
Anode Installation	72000									72000
MAINTENANCE EXPENSE										
Anode Replacement		0	0	0	0	160000	0	295000	0	455000
Coating Repairs		0	0	35000	0	47000	64000	88000	0	234000
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	305000	0	0	35000	0	207000	64000	383000	0	994000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	45750	67100	64050	64050	64050					305000
TAX SAVING @ 46%	-21045	-30866	-29463	-29463	-29463	0	0	0	0	-140300
INVESTMENT TAX CREDIT	-30500									-30500
NET CASH FLOW	253455	-30866	-29463	5537	-29463	207000	64000	383000	0	823200
DISCOUNT RATE - % - 12										
DCF	253455	-27558	-23487	3941	-18724	93636	18398	69972	0	0
CUMULATIVE PWAT	253455	225897	202410	206351	187627	281263	299661	369633	369633	369633

NOTES: Assumed escalation rate 8% per year.
Assumed economic life of ship 20 years.
Assumed effect of tank protection system on salvage value of ship = 0.

FWAT/CASH FLOW ANAYSIS

SOFT COATING WITH CATHODIC PROTECTION - ZINC ANODES
ANODE REPLACEMENT AT 4 YEAR INTERVALS - 10% SOFT COATING REPLACEMENT AT 4 YEAR INTERVALS

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	233000									233000
Anode Installation	150000									150000
MAINTENANCE EXPENSE										
Anode Replacement	0	0	0	175000	0	238000	324000	440000	0	1177000
Coating Repairs	0	0	0	35000	0	47000	64000	88000	0	234000
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	383000	0	0	210000	0	285000	388000	528000	(	1794000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	57450	84260	80430	80430	80430					383000
TAX SAVING @ 46%	-26427	-38760	-36998	-36998	-36998	0	0	0	0	-176181
INVESTMENT TAX CREDIT	-38300									-38300
NET CASH FLOW	318273	-38760	-36998	173002	-36998	285000	388000	528000	0	1579519
DISCOUNT RATE - % - 12										
DCF	318273	-34607	-29494	123139	-23512	128919	111540	96463	0	0
CUMULATIVE FWAT	318273	283666	254172	377311	353799	482718	594258	690721	690721	690721

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE3D

PWAT/CASH FLOW ANAYSIS

SOFT COATING WITH CATHODIC PROTECTION - ALUMINUM ANODES
ANODE REPLACEMENT AT 4 YEAR INTERVALS - 10% SOFT COATING REPLACEMENT AT 4 YEAR INTERVALS

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	233000									233000
Anode Installation	72000									72000
MAINTENANCE EXPENSE										
Anode Replacement		0	0	117000	0	160000	217000	295000	0	789000
Coating Repairs		0	0	35000	0	47000	64000	88000	0	234000
LOST REVENUE	0	0	0	0	0	0	0	0	0	0
CASH FLOW B/FIT	305000	0	0	152000	0	207000	281000	383000	0	1328000
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	45750	67100	64050	64050	64050					305000
TAX SAVING @ 46%	-21045	-30866	-29463	-29463	-29463	0	0	0	0	-140300
INVESTMENT TAX CREDIT	-30500									-30500
NET CASH FLOW	253455	-30866	-29463	122537	-29463	207000	281000	383000	0	1157200
DISCOUNT RATE - % - 12										
DCF	253455	-27558	-23487	87219	-18724	93636	80780	69972	0	0
CUMULATIVE PWAT	253455	225897	202410	289629	270905	364541	445321	515293	515293	515293

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE4A

PWAT/CASH FLOW ANAYSIS

TWO COAT EPOXY TANK COATING WITH NO CATHODIC PROTECTION
NO MAINTENANCE WITH 100% COATING REPLACEMENT AND 1% STEEL REPLACEMENT AT 8 YEAR INTERVALS

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	EIGHTH	TWELFTH	SIXTEENTH	TWENTIETH	TOTAL
CAPITAL										
Coating Installation	492000									492000
MAINTENANCE EXPENSE										
Steel Repairs						273000		506000		779000
Coating Repairs		0	0	0	0	868000	0	1607000	0	2475000
Additional Docking Fees						93000		171000		264000
LOST REVENUE										
Days Out of Service						13		13		
Lost Cash Flow						192000		356000		548000
CASH FLOW B/FIT	492000	0	0	0	0	1426000	0	2640000	0	4558000
FIT on Lost Revenue @ 46%	0	0	0	0	0	-88320	0	-163760	0	-252080
ACRS Depreciation %	.15	.22	.21	.21	.21					
DEPRECIATION AMOUNT	73800	108240	103320	103320	103320					492000
TAX SAVING @ 46%	-33948	-49790	-47527	-47527	-47527	0	0	0	0	-226319
INVESTMENT TAX CREDIT	-49200									-49200
NET CASH FLOW	408852	-49790	-47527	-47527	-47527	1337680	0	2476240	0	4030401
DISCOUNT RATE - % - 12										
DCF	408852	-44455	-37888	-33828	-30204	605098	0	452399	0	1319974
CUMULATIVE PWAT	408852	364397	326509	292681	262477	867575	867575	1319974	1319974	1319974

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE4B

PWAT/CASH FLOW ANAYSIS

TWO COAT EPOXY TANK COATING WITH NO CATHODIC PROTECTION
MAINTAIN COATING AT 5 YEAR INTERVALS WITH 100% REPLACEMENT AT 15TH YEAR - NO STEEL REPAIRS

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	TENTH	FIFTEENTH	TWENTIETH	TOTAL
CAPITAL									
Coating Installation	492000								492000
MAINTENANCE EXPENSE									
Steel Repairs		0	0	0	0	0	0	0	0
Coating Repairs		0	0	0	32000	105000	1547000	0	1684000
Additional Docking Fees		0	0	0	0	0	0	0	0
LOST REVENUE									
Days Out of Service							6		
Lost Cash Flow							152000		152000
CASH FLOW B/FIT	492000	0	0	0	32000	105000	1699000	0	2328000
FIT on Lost Revenue @ 46%	0	0	0	0	0	0	-69920	0	-69920
ACRS Depreciation %	.15	.22	.21	.21	.21				
DEPRECIATION AMOUNT	73800	108240	103320	103320	103320				492000
TAX SAVING @ 46%	-33948	-49790	-47527	-47527	-47527	0	0	0	-226320
INVESTMENT TAX CREDIT	-49200								-49200
NET CASH FLOW	408852	-49790	-47527	-47527	-15527	105000	1629080	0	1982561
DISCOUNT RATE - % - 12									
DCF	408852	-44455	-37888	-33828	-9867	37864	333342	0	654020
CUMULATIVE PWAT	408852	364397	326509	292681	282814	320678	654020	654020	654020

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

CFCASE4C

PWAT/CASH FLOW ANAYSIS

TWO COAT EPOXY TANK COATING WITH NO CATHODIC PROTECTION
NO MAINTENANCE WITH 100% COATING REPLACEMENT AND 1% STEEL REPLACEMENT AT 10TH YEAR

YEAR	FIRST	SECOND	THIRD	FOURTH	FIFTH	TENTH	FIFTEENTH	TWENTIETH	TOTAL
CAPITAL									
Coating Installation	492000								492000
MAINTENANCE EXPENSE									
Steel Repairs						318000			318000
Coating Repairs		0	0	0	0	1012000	0	0	1012000
Additional Docking Fees						108000			108000
LOST REVENUE									
Days Out of Service						13			
Lost Cash Flow						224000			224000
CASH FLOW B/FIT	492000	0	0	0	0	1662000	0	0	2154000
FIT on Lost Revenue @ 46%	0	0	0	0	0	-103040	0	0	-103040
ACRS Depreciation %	.15	.22	.21	.21	.21				
DEPRECIATION AMOUNT	73800	108240	103320	103320	103320				492000
TAX SAVING @ 46%	-33948	-49790.4	-47527.2	-47527.2	-47527.2				-226320
INVESTMENT TAX CREDIT	-49200								-49200
NET CASH FLOW	408852	-49790.4	-47527.2	-47527.2	-47527.2	1558960	0	0	1775440
DISCOUNT RATE - % - 12									
DCF	408852	-44455	-37888	-33828	-30204	562176	0	0	824653
CUMULATIVE PWAT	408852	364397	326509	292681	262477	824653	824653	824653	824653

NOTES: Assumed escalation rate - 8% per year.
Assumed economic life of ship - 20 years.
Assumed effect of tank protection system on salvage value of ship - 0.

ANNEX A
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ANNEX B

American Bureau of Shipping Letter

American Bureau of Shipping
Sixty-five Broadway
New York, N. Y. 10006

Refer to ESW/ad

24 June 1980

File Ref T-10
Steel Rules
Corrosion Control

Cathodic Protection

Offshore Power Systems
Box 8000
Jacksonville, FL 32211

Attention: Mr. Benjamin S. Fultz,
Project Manager,
Research & Development

Gentlemen:

Your letter of 18 June addressed to Mr. Bates was referred to me for reply.

ABS Rules 22.1.7 state "Where special protective coatings are applied to the boundaries and internal framing members of tank spaces, or other effective methods are adopted as a means of corrosion control, reductions in scantlings may be permitted...."

Cathodic protection has been accepted as complying with the Rules as another effective method. However, in numerous cases, despite being in association with a partial coating system, cathodic protection has been ineffective in reducing corrosion.

A number of reasons may be offered for a cathodic system being ineffective. A few of them are:

1) The ballast water may be fresh or brackish with insufficient electrolyte.
2) The ballast tanks may be only partially filled and the anodes are not submerged.
3) The anodes may not be renewed when they are wasted.
4) The anodes may become coated with mud from muddy ballast water and become ineffective.

The American Bureau of Shipping is considering excluding tanks "protected" by cathodic systems from the provisions in the Rules permitting reduced scantlings. It is being contemplated that coatings in ballast tanks may be required.

Very truly yours,
AMERICAN BUREAU OF SHIPPING
W. M. Hannan - Vice President

E. S. Wenzel

E. S. Wenzel
Assistant Vice President

ANNEX C
United States Coast Guard Letter

DEPARTMENT OF TRANSPORTATION

UNITED STATES COAST GUARD

MAILING ADDRESS:
U.S. COAST GUARD (G-MMT-2)
WASHINGTON, DC 20593
PHONE:
(202) 426-2160

16703/46/35

28 JUL 1980

Offshore Power Systems
Attn: Mr. Benjamin Fultz
8000 Arlington Expressway
Box 8000
Jacksonville, Florida 32211

Gentlemen:

Subj: Cathodic Protection

Ref: (a) Your letter of 15 May 1980

Your above referenced letter requested assistance in identifying and documenting Coast Guard restrictions on the use of cathodic protection systems in ballast tanks. Our only requirements for cathodic protection systems are contained in 46 CFR 35.01-25, a copy of which is enclosed. However, these requirements only apply to cargo tanks.

If you have any further questions, feel free to contact us.

Sincerely,

A. E. Henn

A. E. HENN
Commander, U.S. Coast Guard
Chief, Engineering Branch
Merchant Marine Technical Division
By direction of the Commandant

Encl: (1) Tank Vessel Regulations, CG-123

SPEED LIMIT 55
It's a law we can live with.